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DUST RESPIRATORS

THEIR CONSTRUCTION AND FILTERING EFFICIENCY

BY

S. H. KATZ, G. W. SMITH, and E. G. MEITER

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CONTENTS

	Page
Introduction	1
Injurious air-borne dusts and their effects	1
Respirators in use	3
Acknowledgments	4
History of dust respirators	4
Previous investigations	6
Great Britain	6
South Africa	7
Germany	8
United States	8
Some respirators used in industry	9
Respirators with sponge filters	10
Respirators with paper filters	11
Respirators with felt filters	12
Respirators with cloth filters	13
Fogler flat felt filter	16
Gas masks with filters	18
Helmets and oxygen-breathing apparatus	21
Method and apparatus for testing the filtering efficiency of dust respirators	21
Tobacco smoke as a testing medium	21
Preparation of tobacco	23
Mounting the respirator	23
Measurement of tobacco smoke	23
The Tyndall box	25
Silica dust as a testing medium	26
Size of smoke and silica particles used in testing	26
Procedure in optical measurements	27
Accuracy of filtering measurements	27
Filtering efficiencies of industrial dust respirators	29
Tests with tobacco smoke	31
Tests with silica dust	32
Comparison of filtering efficiencies of fabrics	33
Effect of increasing plies of fabric in filter	34
Cause of higher efficiencies of filters with fewer plies	40
Variation in size of particles	40
Electrical charges on particles	40
Summary	41
Effect of deposited smoke and dust on the action of the filter	41
Resistance of fabric filters to the flow of air	43
Comparison of efficiencies of fabric filters with their resistances to flow of air	44
Filtering efficiencies at different rates of air flow	46
Properties of filters and design of dust respirators	46
Comparison of clogging of respirator fabrics	47
New type of dust respirator	47
Filter	49
Efficiency	49
Summary and conclusions	50

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ILLUSTRATIONS

		Page
FIGURE 1.	Respirator with sponge filter inclosed in metal body having pneumatic rubber face-contact	10
2.	Respirator with sponge filter inclosed in rubber body	10
3.	Respirator with paper filter held in support of rubber and metal	11
4.	Respirator with paper filter held in metal body having pneumatic rubber face-contact	11
5.	Respirator with felt filter, metal body, and pneumatic rubber face-cushion	12
6.	Respirator with body of felt; all the felt surface is used as a filter	13
7.	Respirator that covers the whole face, protecting the eyes as well as the respiratory organs; the entire outer covering of felt serves as a dust filter	14
8.	Respirator made of fabrikoid with silk gauze and cheesecloth filter	14
9.	Cone-shaped respirator of fly screen covered with two layers of cotton flannel	15
10.	Respirator of absorbent cotton quilted between cheesecloth	15
11.	Homemade respirator of cheesecloth	16
12.	The Fogler flat felt filter and mask	17
13.	Details of Army gas-mask canister with absorbent cotton filters	18
14.	Painter using air brush and wearing gas mask	19
15.	Helmet used by sand blaster, supplied with dust-free air through a hose	20
16.	Apparatus for testing filtering efficiency of dust respirators with tobacco smoke or air-floated silica dust	20
17.	Apparatus for testing dust respirators with tobacco smoke or silica dust	22
18.	Nozzle for producing smoke streams for examination in Tyndall apparatus	24
19.	Apparatus for measuring resistance of respirators to flow of air	28
20.	Flange for holding fabric so as to expose an area of 100 square centimeters for filtering tests	34
21.	Increased filtering efficiencies of fabric filters against tobacco smoke as the plies of fabric are increased	35
22.	Increased filtering efficiencies of fabric filters against silica dust as plies of various fabric are increased	35
23.	Charts showing that each ply of fabric in multiple-ply filters retains about the same proportion of the smoke or dust that penetrates to it	38
24.	Increased filtering efficiencies of three fabrics as silica dust was deposited upon them	42
25.	Increased resistance of filters as layers of fabric are increased	44
26.	Resistance of three filters to air flowing at various rates, before and after testing against silica dust	44
27.	Filtering efficiencies of multiple ply fabric filters with their resistances to flow of air	45
29.	Bureau of Mines dust respirator designed for low resistance	
28.	Details of the Bureau of Mines dust respirator and high filtering efficiency	48 49

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DUST RESPIRATORS: THEIR CONSTRUCTION AND FILTERING EFFICIENCY

By S. H. Katz, G. W. Smith, and E. G. Meiter

INTRODUCTION

INJURIOUS AIR-BORNE DUSTS AND THEIR EFFECTS

In its investigations relating to the safety and health of workers in the mineral industries the Bureau of Mines has given attention to the danger from breathing dusts, the means by which the workers might be protected, and the merits of dust respirators.

Poisonous dusts, such as those bearing lead or arsenic; some rock dusts, such as silica; metallic dusts, including those produced in grinding and polishing shops; and many other dusts, including some organic dusts such as those in textile mills, are injurious when constantly breathed. Hard-rock miners, stonecutters, glassworkers, potters, and metal grinders are particularly exposed to this hazard. Everyone occasionally encounters a dusty atmosphere and experiences discomfort from it even if he suffers no especial harm.

Any dust inhaled into the respiratory passages or lungs can be considered harmful, even if it is not especially dangerous. A very small amount of dust in the air can be tolerated by the human body, mainly because it has means in the respiratory passages for intercepting much of the dust before it reaches the lungs. The chief interceptors are the small hairs which line the nasal passages, and the specialized cells of the bronchial tubes. The moist surfaces of the passageways also retain particles that lodge upon them. The soluble dusts caught in the air passageways or in the cells of the lungs pass into solution and so are eliminated; the insoluble dusts are mostly eliminated from the lungs and the air passages with the mucus which rises and is expectorated. Some particles that lodge in the alveoli (minute air sacs in the lungs) gradually pass through the tissue, are taken up by certain white blood corpuscles or other cells, and are eventually eliminated or are stored in lymph nodes.

The body, however, has a limited capacity for removing dust particles, and when this capacity is exceeded the lungs become gradually charged with the dusts. As much as 13 grams of silica rock

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dust, numbering 20 million millions of particles,[1] were found in lungs of miners who died from silicosis (fibrosis caused by siliceous rock dust).[2] Examination of silicotic lungs revealed that most of the particles of dust were about 1 micron (1/25,000 inch) in diameter; there was a progressive decrease in the proportion of both larger and smaller sizes. Virtually none exceeded 10 microns in diameter and few were as small as 0.25 micron in diameter, which is about the limit of microscopic visibility.

The dust particles most damaging to the lungs may be considered to be those of the order of 1 micron in diameter. Only a powerful microscope can make such particles visible to the eye; about 50 placed in line would be needed to equal the diameter of a human hair. When such very small particles are dispersed in the air they are carried about like smoke and they settle very slowly from quiet air.

Soluble dusts are most readily eliminated; if their solution in the fluids of the body is innocuous, soluble dusts do least harm. If, however, the dust or the solution formed is corrosive like the dust of the alkalies or poisonous like lead or mercuric dusts, the harm to the body is mainly through the action of the chemical or the poison on the system. Mists, or minute liquid particles, may be classed with the soluble dusts. They are readily eliminated, but may do harm through their chemical action or toxicity.

Air-borne bacteria may be dispersed like dusts. Some disease germs are suspected of spreading through the air and causing infection when inhaled.

Among the insoluble dusts, those of hard rocks, such as silica, or metal dusts are considered most harmful. Over two centuries ago Ramazzinni[3] wrote regarding stonecutters:

> They ofttimes suck in, by inspiration, the sharp, rough, and cornered small splinters or particles that fly off, so that they are usually troubled with a cough, and some of them turn asthmatic and consumptive. Autopsies revealed such heaps of sand, that in running the knife through the pulmonary vesicles he thought he was cutting some sandy body.

Among industrial physicians to-day the same ideas prevail regarding the especially injurious effects of the sharp-cornered and sharp-edged splinters of rock dust of microscopic size.

As most of the injurious particles found in the lungs are approximately 1 micron in diameter, it is evident that an effective respirator must be able to arrest particles of that size.

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[1] Miners' Phthisis Prevention Committee, Final Report: Union of South Africa, Johannesburg, Mar. 15, 1916, p. 17; General Report: Union of South Africa, Johannesburg, Jan. 10, 1916, pp. 139, 140.

[2] Sayers, R. R., Silicosis Among Miners: Tech. Paper 372, Bureau of Mines, 1925, 24 pp.

[3] Ramazzinni, B., [A Treatise of the Diseases of Tradesman]. English translation from the Latin. London, 1705, 274 pp.

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RESPIRATORS IN USE

Dust respirators, or filters to prevent inhalation of dust, have been used in various forms for generations. Of course, it would be best to prevent the formation of dust, or to remove it at the source before it arises into the air, but this is not always practicable. In some dusty processes the means for satisfactorily removing the dust has not yet been developed. Since the dust can not be eliminated, the next protective measure is the use of respirators. The respirators that have been devised are imperfect, but such protection as they do afford is of benefit.

A source of considerable annoyance to the wearers of many types of respirators has been the resistance to air flow. This imposes extra effort in breathing and may become excessive. Some other discomforts may become pronounced, such as the pressure at the edges in contact with the face; the heat caused by the face cover; the warm, humid exhaled air in contact with the face; rebreathing the trapped exhaled air; and the preventing of cooling evaporation and radiation. In cold weather the heat effects are not uncomfortable. Some respirators fit the face so poorly that much of the air is inhaled through openings between the face and respirator without removing the dust. However, despite the lack of perfection in any one type of respirator, the respirators on the whole have been of much value.

Thompson [4] described the situation as follows:

> I do not believe in placing too much reliance upon patent respirators. In some industries they are well enough for temporary use, and it should be made compulsory to wear them, as in going in to empty the "blue beds" of lead carbonate or to clean out pottery kilns or cement tubes. But for ordinary constant use as a protection, for instance, in emery grinding, they are most fallacious. Workmen will not wear them for any length of time, and one as often sees the respirator hung around the workman's neck as one sees his goggles worn over the forehead. Respirators are unbearably warm in hot weather; they soon become clogged and the workman can not talk or expectorate his tobacco juice with satisfaction. Women particularly are most reluctant to wear them, perhaps for the former of these reasons. It is far better, whenever possible, to rely upon other means of dust protection, for the workman is notoriously careless in protecting himself.

In the development of gas masks for industry the Bureau of Mines has made gas-mask canisters with two filters of cotton wool, each one-eighth to one-fourth inch thick between wire screens. These masks gave good protection against such smokes as those produced by ordinary fires in carbonaceous matter [5]—wood, coal, cotton, paper,

[4] Thompson, W. G., "The menace of the dusty trades": Am. Jour. Pub. Health, vol. 7, 1917, pp. 731–741.

[5] Fieldner, A. C., Katz, S. H., and Kinney, S. P., Gas Masks for Gases Met in Fighting Fires: Tech. Paper 248, Bureau of Mines, 1921, 61 pp.

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and the like. The fireman's gas mask[6] requires only the two cotton filters to protect against smokes so dense that the hand is invisible before the face (the cotton-wool filters do not stop the passage of gases or vapors; chemical absorbents are required). Laboratory measurements of the filtering efficiency of the canisters showed that an efficiency of only 50 per cent against tobacco smoke was enough for industrial gas masks. The gas masks have often been used successfully for protection against very dense suspensoids in air or those somewhat difficult to arrest, but the masks are too heavy and cumbersome for general or continued use as dust respirators. For that reason the Bureau of Mines turned its attention to the simpler respirator.

Many industrial dust respirators were tested for filtering efficiency, as were many fabrics and filtering materials. Finally an attempt was made to build a respirator that would have a filtering efficiency equal to that of the gas mask, but would be lighter and more convenient to wear.

This paper describes some of the popular forms of dust respirators found on the market, and gives the results of laboratory tests of the respirators and fabrics. It also describes a new dust respirator of higher dust-removing efficiency developed as a result of the tests.

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HISTORY OF DUST RESPIRATORS

Respirators, or filters to prevent the inhalation of dust, have been used in various forms for centuries. Pliny the Elder[7] mentions attempts to avoid dust inhalation by means of respirators as follows:

> Those employed in the works preparing vermillion cover their faces with loose bladder skins that they may not inhale the pernicious powder, and yet may see through the skin.

---

[6] Katz, S. H., Bloomfield, J. J., and Fieldner, A. C., The Universal and the Fireman's Gas Masks: Tech. Paper 300, Bureau of Mines, 1923, 22 pp.

Steidle, Edward, "The fireman's gas mask and its use." Paper read before a meeting of the Internat. Assoc. of Fire Eng., Louisville, Ky., Sept. 29–Oct. 2, 1925, 36 pp.

[7] Plinius Secundus, C., Historiae Naturalis. Lib. 33, sec. 11.

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More than 200 years ago Ramazzini [8] wrote regarding glass makers as follows:

> * * * all of which they reduce to an impalpable powder, and mix it with the glass in order to make a paste. Now, while this is adoing, though they cover and turn away their face, they can't avoid receiving the noxious exhalations at the mouth; nay, it sometimes falls out that they fall down dead, or are suffocated, or in progress of time are tortured with ulcers in the mouth, gullet, and windpipe, and at last die, consumptives with ulcers in their lungs, as 'tis manifest from dissection of their corpses.

Physicians advised mouth and nose coverings more than 100 years ago,[9] but did not appear to consider them for the purpose of excluding dust, but rather for "tempering" the air in its passage to the lungs. The warmth and moisture of the exhaled air accumulated in the folds of the respirator, was in turn imparted to the inhalations, and thus served to ameliorate the drying or chilling of the respiratory passage or lungs when dry or cold air was encountered. The result, as it affected the breathing, seemed to simulate a mild warm climate, such as was known to be beneficial to those afflicted with respiratory diseases. The idea was elaborated by J. Jeffrys,[10] who published a treatise in 1836. Jeffry's respirator was a "lattice" construction of gold and silver wire. Different sizes of wire and spacing were used in the building up of the "packet"; some wires were as small as 1/600 inch in diameter spaced 1/600 inch apart. The packet was supported over the mouth in the "oral" type, or over the mouth and nose in the "orinasal" type, by means of a silk-scarf holder tied around the head.

A dust respirator [11] designed to filter dusts or injurious substances from the inhaled air was patented in the United States in 1849. The filter was of woolen fabric or other porous substance. The respirator could be fitted to either the nose or mouth, and "clapper valves" directed the flow of air on inhalation and exhalation. Since 1849 numerous dust respirators of the filter type have been devised and patented or have been described in technical literature. In 1870 John Tyndall, the eminent English physicist, made an important advance in respiratory protection when he constructed a "fireman's respirator," [12] similar in many ways to the gas masks used during

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[8] Ramazzini, B., [A Treatise of the Diseases of Tradesman]. English translation from the Latin, London, 1705, 274 pp.

[9] Stock, J. E., Memoirs of the Life of Thomas Beddoes, M. D., with an Analytical Account of His Writings. London, 1811, 413 pp.

[10] Jeffrys, J., Observations upon the Construction and Use of the Respirator: An instrument for facilitating the respiration of persons suffering under pulmonary and bronchial affections, by warming the air inspired, and thereby enabling them to breathe freely in the coldest atmosphere; London, 1836, 12 pp.; Respirators: British Patent 6988, July 21, 1836.

[11] Haslett, P., Inhaler or Lung Protector: United States Patent 6529, 1849.

[12] Tyndall, J., "Dust and disease: A discourse delivered in the Royal Inst. of Great Britain": Fragments of Science, London, 1871, pp. 334–335.

Shaw, Capt., "Appliances for enabling persons to breathe in dense smoke or poisonous vapors": Van Nostrand's Eng. Mag., vol. 12, 1875, pp. 427–432.

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the World War. The respirator consisted of a smoke cap or hood of leather to cover the head and a canister of brass, 2 inches in diameter by 4 inches long, to hold materials for purifying the inhaled air. The canister had screens at bottom and top, and between the screens the air passed in order through the following materials: One-half inch of cotton wool (at bottom); one-half inch of fragments of lime; one-half inch of cotton wool; one-half inch of fragments of charcoal; a thin layer of cotton wool; 1 inch of cotton wool saturated with gycerin; and one-half inch of dry cotton wool. A ball check vave permitted exhalation. With this apparatus firemen were enabled to remain in smoke so dense that a single inhalation would have been intolerable without the respirator. Although Tyndall's respirator contained materials similar to those used in modern Army gas masks and in masks widely used in industry to-day, the "activated charcoal" and soda lime in these masks are far better absorbents.[13] Numerous forms of dust respirators have been devised and used since the early ones mentioned above. Most of the modern respirators likewise employed the filtration principle for removal of dust from inspired air; the differences lie mainly in the filtering medium employed and in the method of adapting the filter to the face.

PREVIOUS INVESTIGATIONS

A search for published reports on dust respirators revealed that many papers merely describe particular respirators, saying little about the service respirators render in industry. Many conclusions of previous investigators are of a negative order and seldom compare the service given by the various types. The following reports by others may be mentioned.

GREAT BRITAIN

In one of the reports of the Royal Commission of Great Britain on Metalliferous Mines and Quarries, Sir H. H. Cunningham,[14] the chairman, has an appendix entitled "Memorandum on dust respirators." He says that the efficient respirators were "intolerably hot" and interfered "so completely" with respiration that it was impossible to wear them in practice. A respirator was designed which consisted of a cup-shaped bag stuffed with wool; it was held over the

[13] Lamb, A. B., Wilson, R. E., and Chaney, N. K., "Gas mask absorbents": Jour. Ind. and Eng. Chem., vol. 11, May, 1919, pp. 420–438.

Fieldner, A. C., Katz, S. H., and Kinney, S. P., Gas Masks for Gases Met in Fighting Fires: Tech. Paper 248, Bureau of Mines, 1921, 61 pp.

[14] Cunningham, H. H., "Memorandum on dust respirators": Report of Royal Commission on Metalliferous Mines and Quarries, Appendix to 1914; Iron and Coal Trade Rev., vol. 89, 1914, p. 80.

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nose and mouth by means of a bent wire frame on the outside and an elastic around the head. These conclusions are offered:

1. That fibrous material either loosely woven or in flock is better for a respirator than closely woven material.
2. That soft respirators are more comfortable than hard ones. They should be tolerably easy to remove to admit removing mucus and saliva from nose and mouth, and be rather soft so as not to impede the wearer.
3. That no perfect respirator can be devised which will keep out all dust and yet allow of breathing during hard work.
4. That even a comforter wound once or twice over the mouth and nose will exercise a very beneficial effect in preventing inhalation of dust.

SOUTH AFRICA

After years of intensive study of the dust problem, the Miners' Phthisis Prevention Committee of the Union of South Africa said: [15]

Respirators no doubt add to the comfort of the wearer in so far as irritation to the passages of the nose and throat are concerned, and may even have a slight value in preventing dust inhalation into the lung by assisting such passages to keep in normal condition and thus act as dust catchers to a better extent than when irritated or inflamed. Such a gain in comfort, however, must not be mistaken for a beneficial result in relation to the prevention of miner's phthisis, which is so insidious that many persons are unaware of the fact that they have contracted it until it is far advanced.

In a later report [16] the committee refers to respirators as follows:

The committee referred to the question of respirators in paragraphs 114 to 119 of its general report. Since the issue of that report other respirators of a different type to those previously submitted have been devised, and some of them are described below. The committee does not place great reliance upon any respirator. It considers that, even although, as a dust catcher, the respirator may be perfect, it will be difficult, if not impossible, to induce underground workers to wear them. A tight fit to the face is still an unsolved problem. A sounder principle appears to be to diminish dust to safe limits and make a respirator unnecessary. In certain classes of work, however, such as mine sampling, it appears unavoidable to make rather more dust than can be considered noninjurious, and the use of a suitable respirator is then advisable. Moreover, if any person working underground will take the trouble to wear a respirator such usage will undoubtedly diminish the amount of dust entering his lungs and should not be discouraged, but it is essential that the user should have the best respirator possible at his disposal. The committee has, therefore, tested such respirators as were brought to its notice, and a description of these is given below.

The committee described three respirators that it considered best; in two forms—Weston's respirator and Toomb's respirator—the air passes through zigzag, baffled passages and impinges against

[15] Miners' Phthisis Prevention Committee, General Report: Union of South Africa, Johannesburg, 1916, 197 pp., par. 119.
[16] Miners' Phthisis Prevention Committee, Final Report: Union of South Africa, Johannesburg, Jan. 10, 1919, 110 pp., par. 143.

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surfaces coated with petrolatum or oil. The petrolatum retains dust impinged against the surface. A face mask or a mouthpiece is used with these dust restrainers. In Taytasack's respirator the air breathed bubbles through a small amount of oil or water held in the receptacle.

GERMANY

German laws require the wearing of dust respirators in certain dusty occupations in the chemical industry, but do not specify particular types of respirators.[17] Schablowski examined 70 different respirators in the laboratory and tested, by a bacteriological method, their filtering efficiencies while worn by men. The test was made by impregnating dusts with spores and blowing the dusts into the air of a small chamber. Two men breathed the dusty air; both held cotton plug filters in their nostrils; one wore a test respirator, the other wore none. After one minute the cotton was removed from the nostrils and the bacteria were determined after an incubation process. The results expressed the percentage of dust passing the respirators. Schablowski found the respirators 11 to 93 per cent efficient in retaining dust. Check valves, which usually were found very inefficient, and the poor fit of respirators were often responsible for the failure to retain much dust. Two of the best were these: (1) A mask of fine cambric or "Muellertuch" made to cover the entire face and head and tie around the neck, with eye pieces inserted in it and a wire frame to hold the fabric from contact with nose and mouth;[18] (2) a mask with felt body and felt edge in contact with the face, and a filter of "fenzystoff" fabric appended in sack form to give large filter surface.

UNITED STATES

In the zinc-lead mines of the Joplin district, Mo., where lung diseases due to rock dust (cherty limestone) were prevalent, the investigators[19] of the United States Bureau of Mines found that the miners would not use respirators unless conditions were unusually bad.

The committee on industrial poisons of the National Safety Council, A. L. Watson, chairman, at the Eleventh Annual Safety Congress, at Detroit, Mich., August 30, 1922, presented a report entitled, "Dust respirators in industry."[20] The committee empha-

[17] Schablowski, Dr., "Über Respiratoren bei gewerblichen Staubarbeiten": Ztschr. Hygiene u. Infekt., Bd. 68, 1911, pp. 169–192.

[18] Kobrak, E., "Respiratoren zum Schutze gegen die Einatuning infektiöser Tröpfchen und Stäubchen": Ztschr Hygiene u. Infekt., Bd. 68, 1911, pp. 157–168.

[19] Higgins, E., Lanza, A. J., Laney, F. B., and Rice, G. S., Siliceous Dust in Relation to Pulmonary Disease Among Miners in the Joplin District, Missouri: Bull. 132, Bureau of Mines, 1917, 116 pp.

[20] Watson, A. L., "Dust respirators in industry": Proc. Nat. Safety Council, 1922, pp. 260–268.

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sized the harmful effects of dust; pointed out that existing respirators had weaknesses that hindered more extensive use; compared values of different respirators; and stated the requirements necessary for respirators which will prove satisfactory to the men expected to wear them. The report said that the problems of each of the many dusts are specific, and that the type of respirator to be used depends on the severity of the conditions and the kind of dust to be eliminated. Skin irritation caused by the contact of the respirators was found to be one of the main reasons why the workmen objected to wearing respirators. In conclusion, the committee stated that:

In spite of the large variety of respirators marketed, we find a great many men working in dusty atmospheres and using no filtering apparatus whatever, and a great many more using handkerchiefs, rags, waste, flannel, etc., evidently in preference to the more pretentious types of respirators—placing comfort before efficiency in results. We believe that there are very few respirators being used as compared with the number of existing dusty jobs where they should be used, and it would seem obvious that the reason for this must be that available types of respirators do not satisfactorily meet the requirements.

The following desirable qualifications in respirators were then listed by the committee: (1) Lightness in weight; (2) automatic adjustment to facial lines; (3) comfortable contact edges which will not irritate; (4) no obstruction to vision; (5) no interference with wearing of goggles; (6) no serious resistance to breathing; (7) relief valve that will not clog; (8) no interference with chewing and spitting; (9) relief valve placed so as not to blow dust in eyes; (10) headbands durable and easy to fasten; (11) inflation valves easy to operate if contact is pneumatic; (12) durability of parts requiring adjustment; and (13) little attention required.

E. H. Brown [21] declares that the respirator is one form of accident prevention in which we have not "made good."

Thus the problem of respiratory protection from air-borne dusts by means of respirators is far from a satisfactory solution. The present writers, however, are of the opinion that the types of respirators now in use are of considerable benefit, and that improvements can be made in respirators to enhance their good qualities.

SOME DUST RESPIRATORS USED IN INDUSTRY

Reference to patent literature discloses numerous types of dust respirators, most of which are based upon the filter principle. All of the major European countries and the United States have issued many such patents; this fact shows the universality of the dust

[21] Brown, E. H., "Consider the respirator": Nat. Safety News, vol. 10, October, 1924, pp. 37–40.

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problem and indicates the amount of thought that has been given it. The scope of this paper does not include mention of more than a few respirators and descriptions of most of the important features of some popular types.

FIGURE 1.—Respirator with sponge filter inclosed in metal body with pneumatic rubber face-contact

RESPIRATORS WITH SPONGE FILTERS

Figure 1 shows a respirator with inclosed sponge filter. The body or frame is of sheet aluminum and is held in position by an adjustable band around the head. A pneumatic rubber-cushion edge is in contact with the face; on the upper side is a metal disk check valve for the emission of exhaled air. The seven holes in the frame front are backed by a bronze-wire screen filter of fine mesh, and the sponge, which may be wet if desired, is stuffed into a pocket behind the screen, so that it fits the pocket closely. The wet sponge can absorb small quantities of water soluble gases, such as ammonia or hydrochloric acid gas. However, the gas-absorbing properties of the small amount of water are so slight, even of the favorable gases mentioned, that the respirator is in no sense a substitute for gas masks as a protection against gases.

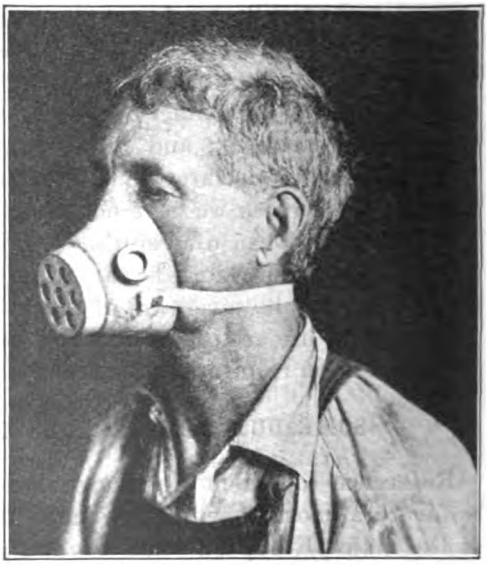

FIGURE 2.—Respirator with sponge filter inclosed in rubber body

Figure 2 shows a respirator of similar construction, but molded of white rubber. The holes are backed by a gauze filter cloth sewed to a rubber ring, and a sponge is held in the pocket behind the cloth. The edges of the rubber body

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itself lie against the face. The entire respirator may be washed in water or disinfectants and not be corroded.

RESPIRATORS WITH PAPER FILTERS

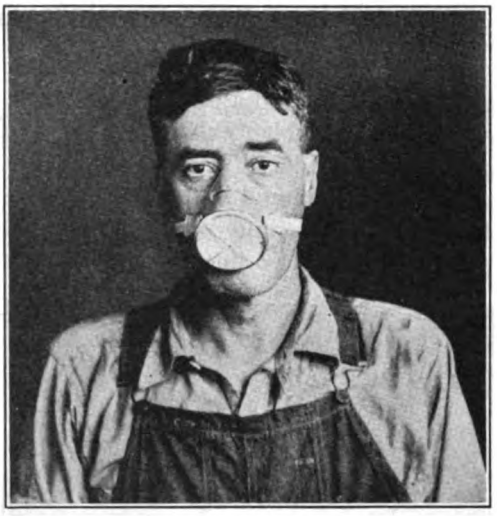

FIGURE 3.—Respirator with paper filter held in support of rubber and metal

Figure 3 shows a dust respirator that is now in fairly wide use. The body is made of molded white rubber with thin edges, formed to lie parallel against the face. At the outer end is an adapter of sheet aluminum, which crimps and binds a circular filter paper of cotton fiber, loose in texture, over an aluminum edge. An arch of stiff metal wire is attached to the rubber body in position over the bridge of the nose. This wire may be shaped by bending it so as to grip the nose and conform to the contours between the nose and cheeks. Leakage of air at these places is a serious defect of many respirators. There is no exhalation valve on this respirator; the breath passes outward as well as inward through the filter; however, this respirator is made with exhalation valves if desired.

FIGURE 4.—Respirator with paper filter held in metal body with pneumatic rubber face-contact

Another respirator with a paper filter is shown in Figure 4. The body of this respirator is of sheet aluminum with a pneumatic rubber cushion adjacent to the face. The exhalation valve is of the mica-disk type. The front has a brass-wire screen in an adapter of aluminum which crimps the paper filter over the circular edge of the frame. The paper is gauzy

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tissue, and 4 to 10 thicknesses are used for a filter. A supply of the paper disks accompanies each respirator.

RESPIRATORS WITH FELT FILTERS

Figure 5 shows a respirator with a felt filter. It has a sheet-aluminum body and a pneumatic rubber face-cushion similar to those described. A rubber exhalation valve of the Bunsen type is attached at the lower side. The felt filters, 6.4 centimeters (2½ inches) in diameter and about 4 millimeters (three-sixteenths inch) thick, are of felt of a cotton and wool mixture, loose in texture. The felt is placed between two fine wire, closely meshed, circular bronze screens which spring into the circular channel. A number of felt filters are supplied with each respirator, so that the filter may be changed when clogging with dust increases the resistance to air flow.

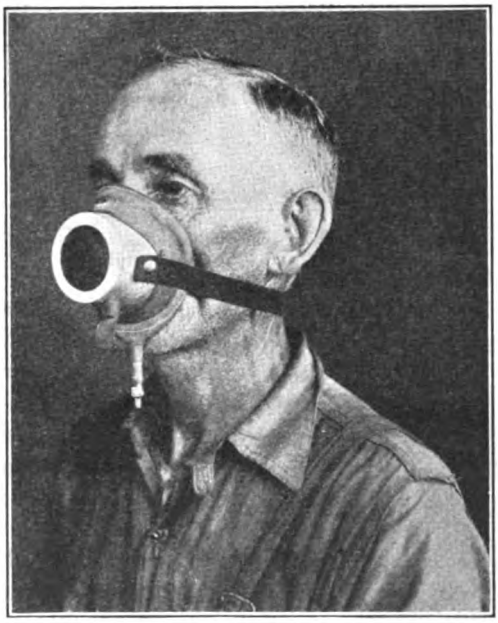

FIGURE 5.—Respirator with felt filter, metal body, and pneumatic rubber face-cushion

All the respirators described heretofore are similar in design, but Figure 6 shows a respirator of English make which introduces new principles. The body, or framework, is woolen felt about 6 millimeters (one-fourth inch) thick, lined with rubberized cloth to prevent the moisture-laden exhalations from wetting the felt. The inhaled air passes through the felt to the space between the felt and the rubberized lining, then through a check valve (rubber-disk type) into the interior space, and thence to the nostrils. Another similar check valve passes the exhalations out. A strip of lead metal is inclosed in a piece of fabric sewed to the respirator at a position over the bridge of the nose; the lead may be modeled to fit the respirator closely to the lines of the face. This respirator provides a broader filtering area than those first described; the resistance to breathing is accordingly reduced and clogging is less rapid. The filter on this respirator can not be changed; if it becomes clogged it must be cleaned by beating, by vacuum cleaning, or by blowing air through it. The

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respirator covers only the mouth and nose and is called a "half mask."

Figure 7 shows an English "full mask" dust respirator embodying the same principle as that just described. The filtering surface is loose woolen felt about 6 millimeters (one-fourth inch) thick, lined with a rubber sheeting (two layers of rubber with cloth vulcanized between) about 2.5 millimeters (one-tenth inch) thick. The air filters into the space between the felt and the rubber sheet, passes through two rubber-disk check valves, one under each eyepiece, and then passes to the nostrils. Exhalations are discharged through a "square" rubber check valve inclosed in the sheet-metal snout. This respirator covers the face and protects the eyes as well as the respiratory organs. Plain glass eyepieces similar to those in a Tissot gas mask facepiece are set into the respirator—in fact, the entire construction of facepiece and head straps is similar to that of gas masks. The full mask respirator has a larger filtering surface than any of those described, and accordingly it clogs more slowly.

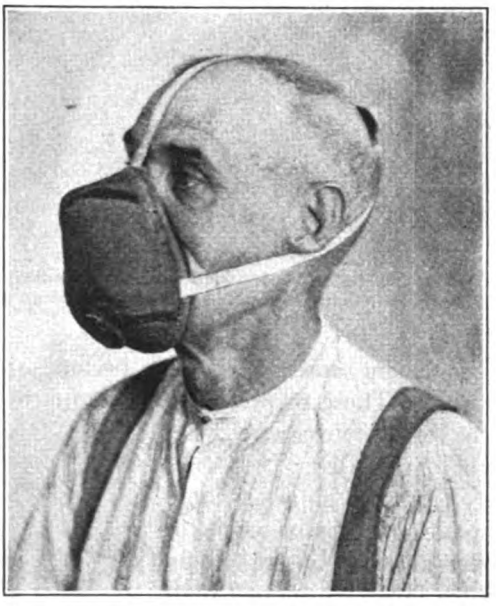

FIGURE 6.—Respirator with body of felt; all the felt surface is used as a filter

RESPIRATORS WITH CLOTH FILTERS

Figure 8 shows a respirator with cloth filter. The body of the respirator is made of pyroxylin fabrikoid, impervious to air. The central part of the fabrikoid is cut away, and the filtering medium, consisting of an outer layer of fine silk gauze over three inner layers of cheesecloth, is sewed into its place. The outer edge of the fabrikoid is bound with tape; at the position of the nose bridge is an extra tape inclosing a wire for bending the respirator to fit the face.

A cone-shaped respirator formed of fly screen with a covering of two layers of cotton flannel is shown in Figure 9. The flannel is bound over the basal edge of the screen and forms the contact with the face. Inhalation and exhalation pass through the flannel cover-

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ing the respirator, which thus presents its entire outer area for filter action. This respirator may be conformed to the face somewhat by bending the screening.

FIGURE 7.—Respirator that covers the whole face, protecting the eyes as well as the respiratory organs; the entire outer felt covering serves as a dust filter

A simple respirator of absorbent cotton quilted between two layers of cheesecloth is shown in Figure 10. The makers designed this respirator especially for painters who use the air brush for spraying paint. The fabric material is gathered above the bridge of the nose to form a sort of nose-fitting pouch. About 5 grams of charcoal granules are sprinkled into the cotton wool for the purpose of absorbing the vapors of paint solvents, but this amount of charcoal is insufficient and its spacing becomes too irregular to be of much value. These respirators are comparatively cheap and are designed to be thrown away when they are soiled.

FIGURE 8.—Respirator of fabrikoid with silk gauze and cheesecloth filter

Figure 11 shows a home-made respirator sent to the authors by an official of a large white-lead manufacturing company. The respirator is made of a cheesecloth strip, 0.45 by 2.4 meters (1½ by 8 feet) folded into six layers; the upper edge is turned over four times, making a somewhat thick fold; this fold is cut in two at the center and cut away from the upper edge for a distance of about 18 millimeters (three-fourths inch) on each side of the center. The severed parts are tucked under the adjacent folds, and the folds

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themselves are gathered above and over toward the center, forming single pleats. The bunched folds or pads thus formed fit into the depressions on each side of the nose. A cotton tape, 1 inch wide by 5½ feet long, is sewed over the folded edge, and all the folds are sewed into place by simple stitching. The sender of the respirator writes as follows:

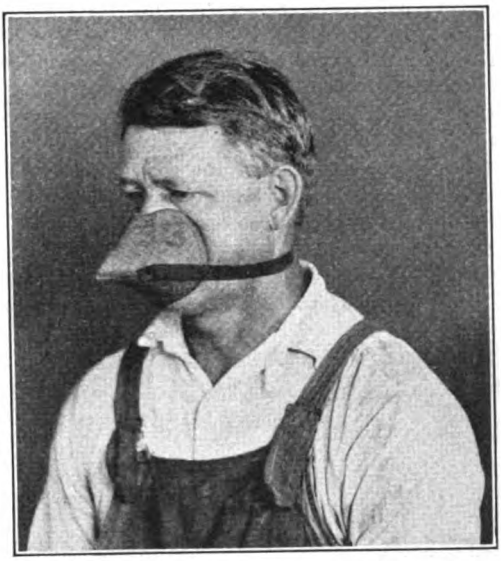

FIGURE 9.—Cone-shaped respirator of fly screen covered with two layers of cotton flannel

In our many years of endeavor to prevent dust reaching the nose and mouth of our employees we have experimented with most every kind of respirator. We have found that all are more or less unsatisfactory, primarily because when a respirator is successful in preventing dusts reaching the nose and mouth * * * the respiration becomes so difficult that the men will not wear them. * * * We have arranged one for our men that has been more satisfactory than any we have ever used. * * * The two pads you will notice at the top of the respirator go one on each side of the nose. The tapes are carried around the head over the ears, across the back of the neck, and come forward and are tied under the chin. Pull the lower part of the apron to the right and left as far as it will go and the six layers of cheesecloth make a very satisfactory filter material. The large number of square inches of surface enable the working men to breathe with comfort. After a man has worn this for a short time and the material becomes saturated with moisture from his breath, it becomes a very satisfactory respirator. At any rate, our men seem to prefer it to any other, and it has been very successful with us.

FIGURE 10.—Respirator of absorbent cotton quilted between cheesecloth

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Another homemade respirator is described by the Department of Labor of the State of New York,[22] as follows:

This homemade respirator consists merely of one-half ounce of clean absorbent cotton pinned, or otherwise fastened, to a piece 5 inches wide of cheesecloth, or of coarsely woven muslin, and of sufficient length, about 33 inches, to tie about the head; or of a length if preferred to cover nose and mouth thoroughly, 7 or 8 inches, to which is attached tape, which can be fastened at back of head, and all dust is filtered out for a period of four hours or more. The absorbent cotton of the respirator should be covered with a small piece of muslin or cheesecloth to prevent the small particles of fiber from touching the lips or tongue of the operator wearing it; the total weight should be about two-thirds ounce.

The tests conducted by the division of inspection as to the efficiency in filtering out and excluding dust by the use of absorbent cotton or clean cotton waste, covered periods of four hours each. Dust-laden air containing a basic lead salt was drawn through the filtrating media of a respirator constructed as described, at a rate equal to the amount of air breathed by an average individual (about 15.6 cubic feet per hour). Careful analytical tests revealed no lead drawn through the gauzy material forming the filtrating material of the respirator.

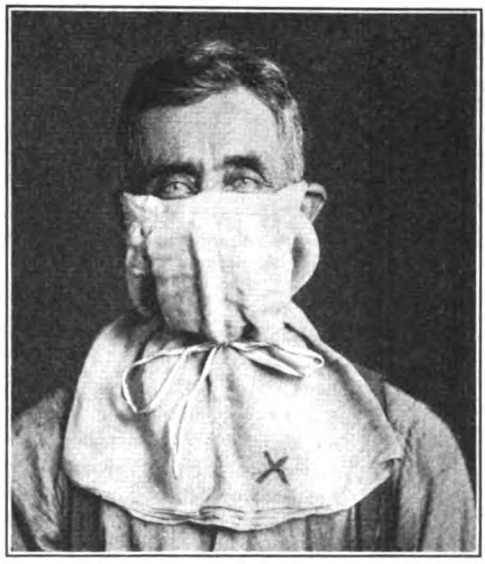

FIGURE 11.—Homemade respirator of cheesecloth

Respirators thus constructed filter out the dust in the air being breathed, are cheap, light in weight, do not obstruct vision, can be changed daily at little cost, and can be washed when necessary. There is less incentive for a workman to appropriate the respirator of another. They neither break, rust, nor wear out. They cause no excessive perspiration and absorb what is produced; cause no irritation of the cheeks, nose, and chin, and can be more readily arranged to fit the face than the patented types. It is recommended, on account of the properties possessed by this form of respirator and superiority described, that this type be accepted in compliance with Rule 722 of the Industrial Code of the Labor Law of New York State.

FOGLER FLAT FELT FILTER

During the World War the intensive thought, talent, and energy of numerous trained investigators were devoted to the problem of protecting soldiers, not only from gases, but also from military suspensoids—minute solid or liquid particles distributed in the

[22] Department of Labor, State of New York, A Simple and Inexpensive Respirator for Dust Protection: Special Bull. 90, December, 1915.

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air as dust or mist clouds. A notably effective protective device developed at the American University, Washington, D. C., first under direction of the United States Bureau of Mines and then under the Chemical Warfare Service, is the Fogler [23] flat felt filter. Figure 12 shows the filter with an attached gas-mask canister and face piece. The haversack that hangs from the neck of the wearer carries the filter and canister, shown on the outside for purposes of illustration. Although these highly efficient filters were not required by the troops, many were made and held in readiness. Later some of them found their way into industries, along with other Army gas masks of well-known types.[24]

FIGURE 12.—Fogler flat felt filter and mask

The Fogler flat felt filter consists of two rectangular pieces of an especially dense woolen felt about 21.6 by 24.1 centimeters (8½ by 9½ inches) by 3 millimeters (one-eighth inch) thick, with a crimped-wire screen separator of slightly smaller dimensions between. On the outside of the felts are two similar crimped screens, both of which are covered with canvas. The fabric and felt edges are all thoroughly rubberized and vulcanized together. Each canvas side is perforated by five holes 1 centimeter (0.39 inch) in diameter. A tube about 2.54 centimeters (1 inch) in diameter passes through one canvas and one felt and connects with the central space between the felts. The air, filtering, passes through the canvas or its perforations, filters through the felt to the central space, passes through the exit tube to an attached canister containing activated charcoal or other gas absorbents, and then goes to the mask for breathing. If protection from dusts only is required, the canister is omitted.

The large filtering area of the Fogler flat felt filter permits breathing through the highly efficient filter without excessive resist-

[23] Fogler, Maj. B. B., in charge of the Mechanical Research Section at the American University, 1917 to 1919, which developed the Fogler flat felt filter.

[24] Fieldner, A. C., Katz, S. H., and Kinney, S. P., Gas Masks for Gases Met in Fighting Fires: Tech. Paper 248, Bureau of Mines, 1921, 71 pp.

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ance to flow of air or rapid clogging. For retaining the very finest suspensoids the Fogler filter is the most effective of the types so far employed in industry.

GAS MASKS WITH FILTERS

The United States Army gas masks used during the World War had canisters containing about 600 cubic centimeters of mixed granular activated charcoal and soda lime, and two filters of cotton wool one-fourth inch thick between wire screens (fig. 13). These were effective in removing not only the military gases, but were also effective in removing the suspensoids of fine dusts and mists of poisonous or asphyxiating solid and liquid particles distributed into the air by explosives. For instance, the so-called sneeze gas (diphenyl chlorarsine), a crystalline solid without an appreciable vapor, was dispersed as minute solid particles through the air by explosive charges in the shells carrying the gas, and the two cotton-wool filters in the canisters were an effective protection. An efficient military dust mask was also developed on the electric precipitation principle,[25] but it was not employed in the field.

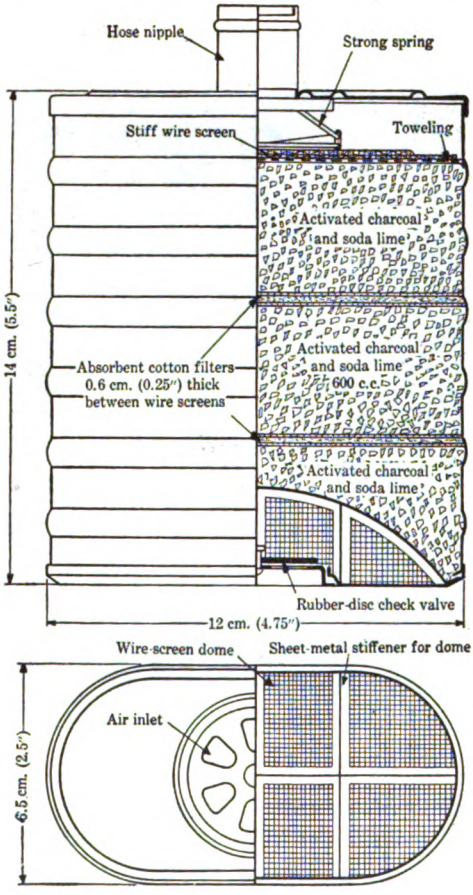

FIGURE 13.—Details of Army gas-mask canister with absorbent cotton filters

Masks similar to the Army gas mask are now much used in industry to protect against such ordinary smokes as wood smoke,[26] and they have been used successfully by painters employing the air brush in especially difficult places.

[25] Strong, W. W., "Electrical fume mask,": Phys. Rev., vol. 14, 1920, pp. 176–177.

[26] Katz, S. H., Bloomfield, J. J., and Fieldner, A. C., The Universal and Fireman's Gas Masks: Tech. Paper. 300, Bureau of Mines, 1923, 22 pp.

Fieldner, A. C., Katz, S. H., and Kinney, S. P., Gas Masks for Gases Met in Fighting Fires: Tech. Paper 248, Bureau of Mines, 1921, 71 pp.

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Figure 14 shows a painting job where gas masks were employed. A large five-story building was filled with bins for the storage of pipe fittings. To paint the bins was difficult, because they were

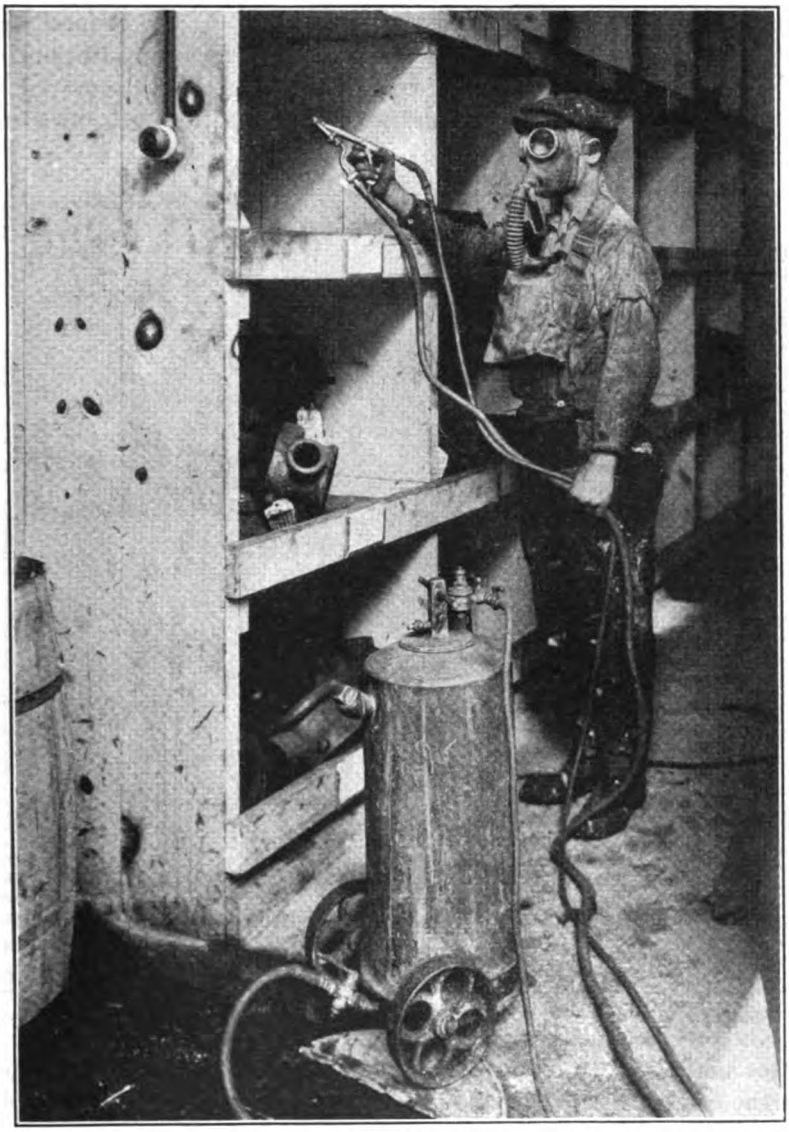

FIGURE 14.—Painter using air brush and wearing gas mask

about 3 feet deep, and many of them were subdivided in small cross sections. For this reason the spray gun was used. The men of necessity had to work with their faces close to the bin openings, and thus they inhaled some paint spray and vapors of the solvents.

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They shortly became sick. Gas masks were obtained, and two men protected by the masks, working alternately in half-hour shifts, finished the entire job without developing any untoward symptoms.

The gas masks had canisters like that shown in Figure 13, except that the granular filling was all activated charcoal, 8 to 14 mesh size, which is the best absorbent for the vapors of benzene, turpentine, and other paint solvents. The two cotton-wool filters removed all of the paint mists. The canisters were changed for fresh ones once during the job.

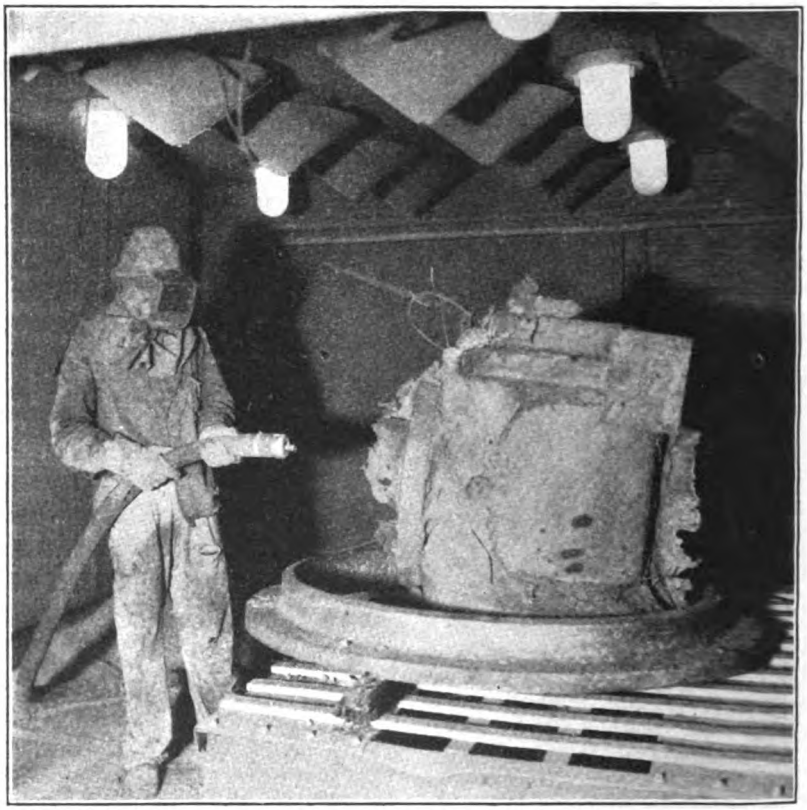

FIGURE 15.—Helmet used by sand blaster; a hose supplies dust-free air to the wearer

Gas masks have been used also as a protection from zinc fumes, but the filters usually clog too rapidly for the masks to be practicable for this purpose.

Gas masks are heavier, have greater breathing resistance, and are more oppressive to wear than the respirators described. For these reasons a person can do less work while wearing a mask than he can without it, but he may work in safety. During the World War it was determined that soldiers forced to wear their masks were only 50 per cent efficient. Workmen who wear masks and their employers

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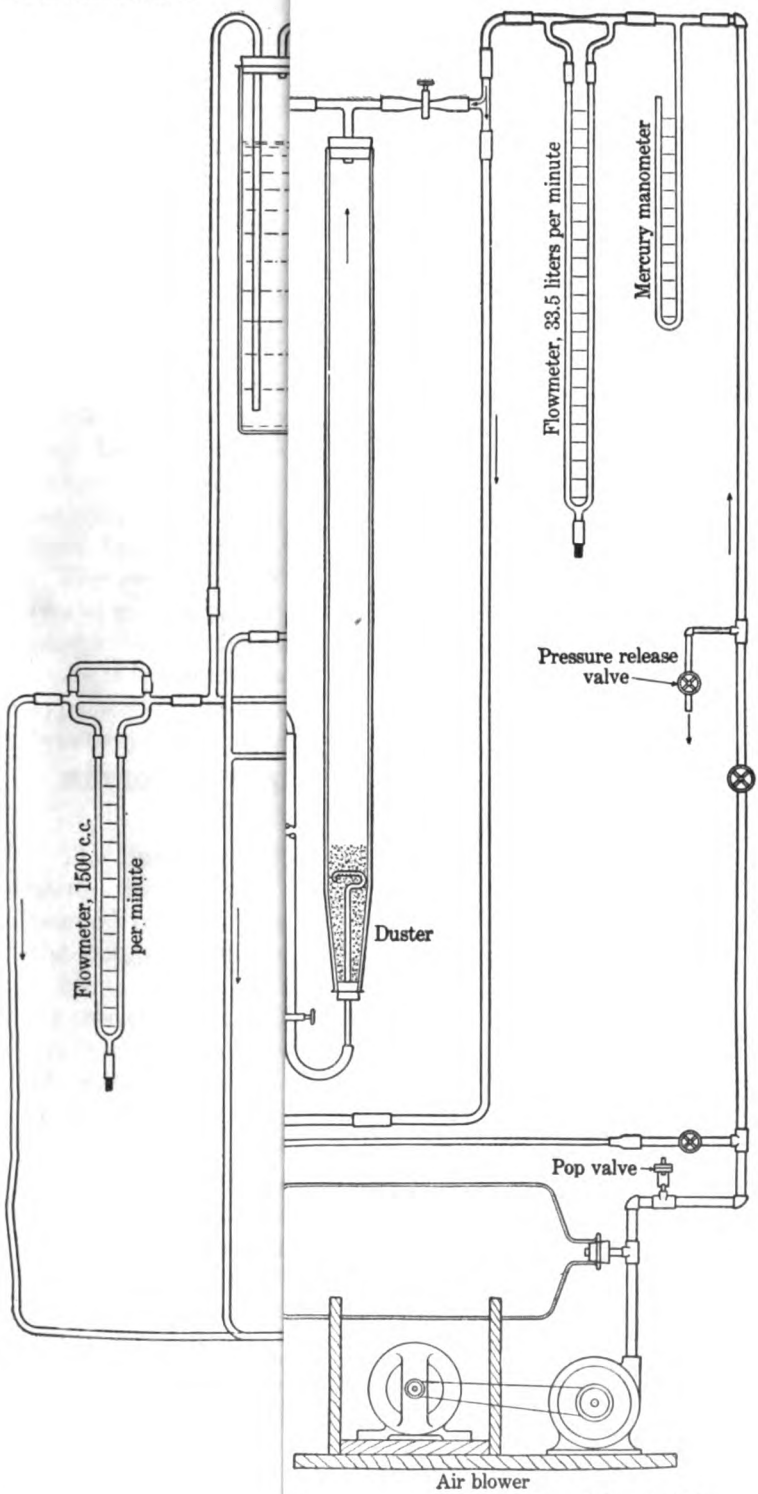

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must recognize and consider this limitation. Alternate periods of work and rest enable to the work in hand to be accomplished safely and without hardship.

HELMETS AND OXYGEN BREATHING APPARATUS

An entirely different principle of dust protection is employed in the helmet covering the entire head (see fig. 15.) Dust-free air from a compressed-air line is supplied to the helmet through a rubber hose. Such helmets are used by sand blasters, whose work creates dense concentrations of dust. An ordinary respirator with a paper or sponge filter is often worn inside a type of helmet which has wire-screened openings in front instead of glass, because the abrasion of the glass by the sand obstructs the vision. Winslow, Greenburg, and Reeves [27] investigated this combination to determine the protection it afforded; they concluded that a respirator inside a helmet supplied with air from a pressure line will effectively guard the sand blaster from dust.

The respirators alone are not effective in sand-blasting work, because, as a rule, they are too inefficient as filters to provide adequate protection and because the dense dust rapidly clogs most of them.

As this paper deals essentially with dust respirators of the filter type, nothing more will be said about helmets, hose masks, or oxygen breathing apparatus—devices which may also afford protection.

METHOD AND APPARATUS FOR TESTING THE FILTERING EFFICIENCY OF DUST RESPIRATORS

The Bureau of Mines tested respirators for filtering efficiency by using the Tyndall beam method.[28] Tobacco smoke or dust suspended in air is passed through a respirator, and the streams of the outgoing and incoming air are compared by viewing them in a beam of light in a dark box. The amount of light reflected indicates the dust. Dilution of the incoming stream with measured portions of dust-free air until the two streams match in intensity of reflected light gives a measure of the filtering efficiency of the dust respirator.

TOBACCO SMOKE AS TESTING MEDIUM

Figure 16 is a diagram of the apparatus for testing respirators by tobacco smoke or by air-floated silica dust; Figure 17 gives a view of this apparatus. The test with tobacco smoke is as follows:

A small motor-driven rotary blower furnishes air under a pressure that is maintained at 10 centimeters of mercury head

[27] Winslow, C.-E. A., Greenburg, L., and Reeves, E. H., "The efficiency of certain devices used for the protection of sand blasters against dust hazard": Public Health Reports, vol. 35, 1920, pp. 518–534.

[28] Fieldner, A. C., Oberfell, G. G., Teague, M. C., and Lawrence, J. N., "Methods of testing gas masks and absorbents": Jour. Ind. and Eng. Chem., vol. 2, 1919, pp. 519–540.

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by regulating a valve on the outlet end of the apparatus. This pressure, which is sufficient to force air through the entire apparatus against the resistance of the respirator and other parts, is measured by a manometer near the pump. Next to the manometer, in the direction of the flow of air, is a flow meter which measures the rate

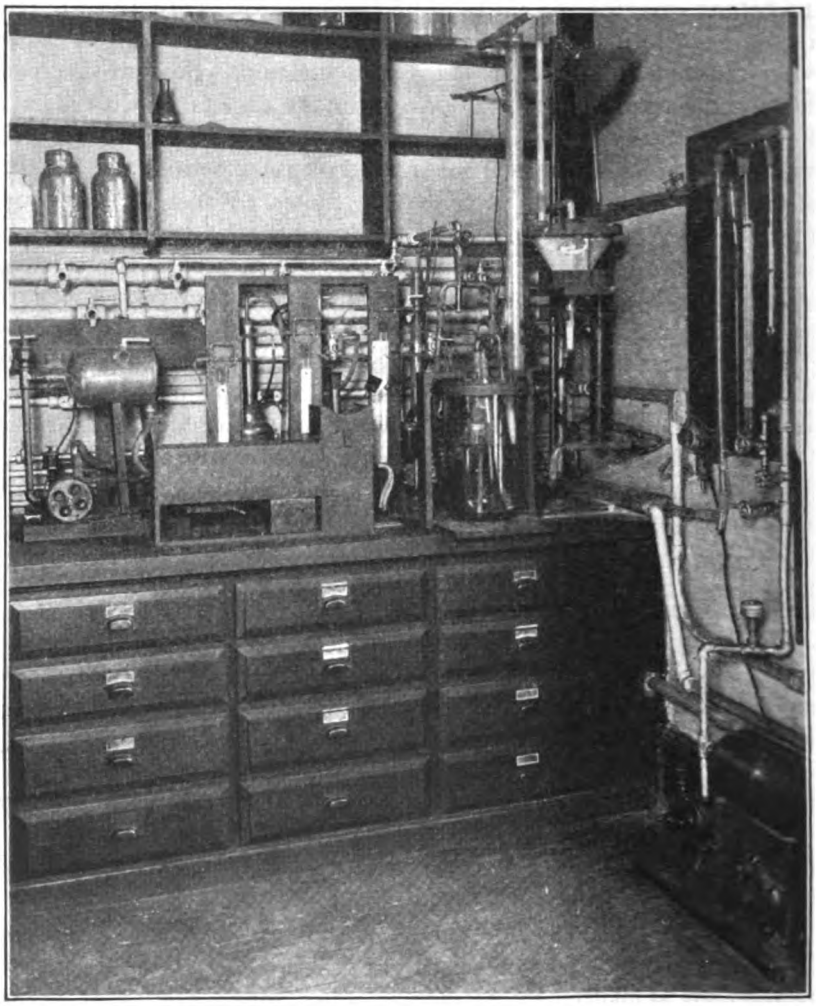

FIGURE 17.—Apparatus for testing dust respirators with tobacco smoke or silica dust

of flow of air. Regulation of the rate is obtained by the valves on the pipes near the pump; 33.5 liters of air per minute are used in respirator testing; 1.5 liters pass off to the Tyndall apparatus, and the remaining 32 liters per minute pass through the respirator. After it leaves the flow meter the air passes through the 2-inch iron pipe, which constitutes the tobacco burner.

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PREPARATION OF TOBACCO

The tobacco used in the test is molded into sticks by the formula given below. Sun-dried tobacco leaf is ground and screened to the sizes needed. The sized material is mixed with potassium nitrate and rosin for binder, as well as for smoke production, in the following proportions:

Formula for tobacco sticks to make smoke for testing respirators

Tobacco:	Grams
20 to 48 mesh	500
48 to 65 mesh	300
65 to 100 mesh	200
Rosin, through 100 mesh	475
Potassium nitrate, through 65 mesh	110

A candle wick is imbedded in the center of the tobacco stick to add strength, and the mixture is pressed into a sheet-iron mold, 1 inch square and 15 inches long, open on one side. The mold is lined with paper to prevent sticking. The mold and mixture are baked on a hot plate under the cover of a half-round of sheet iron, 3 inches in diameter. Each of the four sides of the stick in turn is baked brown; the mold is covered with a strip of sheet metal before it is inverted to bake the exposed side of the stick. Smoke from sticks prepared in this way shows no carbon on the filter, and the ash is free from carbon.

The air and the smoke from the tobacco burners pass through a large jar, where they are mixed, then through a smaller jar containing a wad of cotton wool for filtering out large particles. Next, the mixture is either passed through the respirator and allowed to escape into a hood, or it can be by-passed around the respirator and into the hood.

MOUNTING THE RESPIRATOR

In order to pass the smoke through the respirator it is mounted on a tripod in a glass jar, as shown in Figure 16. The smoke and air are led into the jar and must pass through the respirator to reach the exit tube. The face-contact edge is firmly set in modeling clay to prevent any leakage there; the valves, if present, are stopped, so that the measurement represents the restraining effect of the filter alone without errors due to leakage at facial contacts or valves. However, it is true that leakage at the valves or at the facial contact sometimes reduces the efficiency of the respirator when it is worn; unless the respirator fits the face almost perfectly leakage may render it useless.

MEASUREMENT OF TOBACCO SMOKE

The remaining part of the apparatus is used to measure the proportion of smoke that passes through the respirator. On the tube that leads the air and smoke from the respirator is a small glass

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tube connection (*a*, fig. 16) leading to a stopcock and flow meter, and allowing 1,500 cubic centimeters of filtered air and smoke to pass through a nozzle into a light beam in a Tyndall box. Smoke and air, approaching the respirator at a point just above it in the jar, are drawn through a similar small tube (*b*, fig. 16), stopcock, and

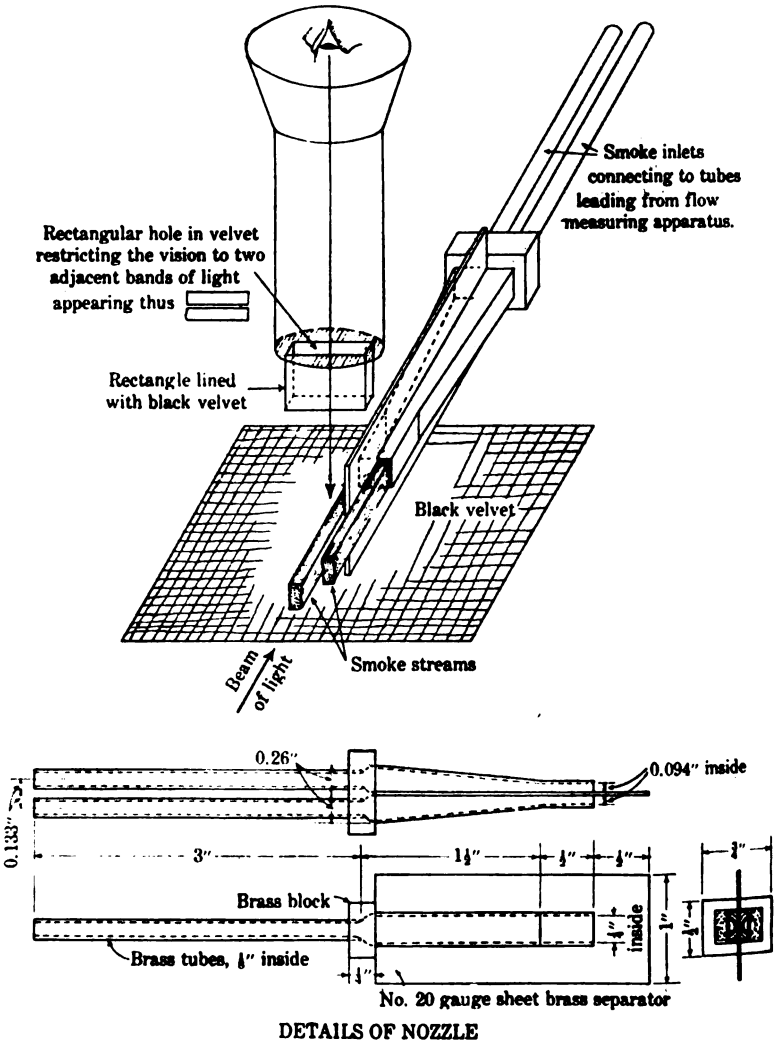

FIGURE 18.—Nozzle for producing smoke streams for examination in Tyndall apparatus

flow meter, and discharge through the nozzle alongside the other smoke stream. The nozzle (finished dead black) is shown in detail in Figure 18; it delivers the two smoke streams of rectangular cross section, 4.8 by 6.4 millimeters (three thirty-seconds by one-fourth inch), in close juxtaposition in order to facilitate comparison. The two systems for conducting the smoke streams to the Tyndall box

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are alike in size and length of tubing, construction, and bends: this similarity causes the systems to have equal effects on the deposition of smoke particles on the walls.

In order to dilute the incoming smoke to match the outgoing smoke, pure filtered air from the pump is passed through a controlling stopcock with a screw and long lever-arm movement for fine adjustments, and through a flow meter calibrated in figures of percentage. Then it is mixed with the incoming smoke before the smoke reaches the 1,500-cubic centimeter flow meter. This flow meter is equipped with the device of Oberfell and Mase,[29] which automatically maintains a constant flow of 1,500 cubic centimeters of gas. When no air is added 1,500 cubic centimeters of undiluted smoke passes through the flow meter; when 1,500 cubic centimeters of air is admitted to the line, only air passes through the flow meter and the smoke passes out of the system through the regulator and escapes into the room. The smoke leaves the line from a point behind that at which the pure air enters; hence there is no mixing of smoke and air before the excess smoke escapes. When any amount of the pure air less than 1,500 cubic centimeters is admitted, it passes through the flow meter with the amount of smoke required to make the sum of 1,500 cubic centimeters, and the residual smoke automatically escapes through the regulator.

The flow meter that measures the pure air is calibrated in percentage figures, 1,500 cubic centimeters being 100 per cent. Thus, when a filter is 50 per cent efficient, or allows half of the incoming smoke to pass through it, a mixture of 50 per cent of smoke and 50 per cent of pure air is required in the Tyndall box to match the stream of smoke from the outgoing side of the filter. After smoke streams have been matched by this arrangement the efficiency percentages of the filters are read directly from the water column in the percentage-calibrated flow meter.

THE TYNDALL BOX

The Tyndall box is made of wood, painted dead black inside. The beam of parallel light, having a direction opposite to that of the streams of smoke in it, is provided by a lens and a 40-candle-power, 16-volt, nitrogen-filled automobile lamp. The voltage is regulated by a small transformer on 110-volt alternating current. To remove excess smoke a suction is maintained on the box. The line of sight passes through a small rectangular opening in the box, lined with black velvet to prevent reflection, and permits observation of about 2 centimeters of the smoke streams just after they have passed from the nozzles. Black velvet covers the bottom of the box opposite the eyepiece.

[29] Oberfell, G. G., and Mase, R. P. "An automatic compensating flow meter": Jour. Ind. and Eng. Chem., vol. 11, 1919, pp. 294-296.

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Before measurements are made, the apparatus is tested blank—that is, without a respirator in place. The smoke streams in the Tyndall box are required to match, and in order to obtain this result the apparatus must be frequently cleaned.

SILICA DUST AS A TESTING MEDIUM

To determine by optical means the efficiencies of respirators in filtering silica dust suspended in air, the same apparatus is used, except the tobacco burner. The air is passed through an accessory apparatus for raising a cloud of dust in the air, as shown in Figure 16. This apparatus consists of a long glass tube 6.25 centimeters (2½ inches) in diameter, tapered at the bottom. The lower opening is stopped with a one-hole rubber stopper through which a narrow glass tube passes to conduct the air. This tube fits in the stopper with sufficient ease for it to be moved up and down without leakage of air; its upper end is sealed and bent into a circle; its under side is perforated with numerous small holes. About 250 grams of silica dust, previously dried at 200 to 300° C., is put into the wide tube. The air is dried with calcium chloride held in a tube preceding the dust tube, because even a small amount of moisture prevents the formation of good clouds. In passing through the small perforations at high velocity the air picks up dust particles and floats them upward. At the top of the wide tube the air and dust pass out through a T; the dust then passes through a centrifugal separator, where larger particles or aggregates are deposited, through a small jar holding a fine screen, and then to the jar containing the respirator.

SIZE OF SMOKE AND SILICA PARTICLES USED FOR TESTING

Wells and Gerke[30] have shown that the particles of tobacco smoke average 0.273 micron in diameter, with an average deviation of 1.8 per cent. The tobacco smoke utilized by Wells and Gerke for the measurements was produced by the same process as that described in this paper. As tobacco-smoke particles are small and uniform in size and have little tendency to clog a filter, they make an excellent medium with which to test the efficiency of a filter in removing very fine particles. Tobacco-smoke particles consist of tar. A distillation analysis of condensed tobacco-smoke tar gave the following result: Up to 170° C., 1.94 per cent by volume of the dry tar: 170 to 200° C., 0.97 per cent; 230 to 270° C., 16.82 per cent; 270 to 350° C., 29.10 per cent; 350° C. to dry, 48.52 per cent; residue by difference, 2.65 per cent.

The silica dust used in these experiments was an especially fine preparation, called "silica smoke" in the trade, made for polishing

[30] Wells, P. V., and Gerke, R. H., "An oscillation method for measuring the size of ultramicroscopic particles": Jour. Am. Chem. Soc., vol. 41, 1919, pp. 312–329.

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and for ceramic purposes. Microscopic examination showed nearly all particles to be of the order of 1 micron (1/25000 inch) in diameter, but they were not of uniform size. Those particles that floated up through the long duster tube and passed through the centrifugal separator were used in testing. Probably many particles were as small as those of tobacco smoke, but most of them were larger.

PROCEDURE IN OPTICAL MEASUREMENTS

Before a respirator was tested against either smoke or silica dust, its resistance to the flow of air was measured in a separate apparatus, the details of which are shown in Figure 19. A flow of 85 liters per minute was taken as the standard rate for resistance measurements. First, the resistance of the tubes attached to the tripod mount for the respirator was determined; then the respirator was fastened upon the tripod with the modeling clay and the resistance was determined again. The increase of resistance was taken as the resistance of the respirator. The tripod with the respirator was placed in the smoke jar, the tubes connected with the Tyndall apparatus, and the filtering efficiency measured. After the filtering efficiency in the tests with silica dust was determined, the resistance was measured again to ascertain the increase caused by clogging with dust.

ACCURACY OF FILTERING MEASUREMENTS

The accuracy of the filtering measurements decreased with the decrease in the efficiency of the respirators. Efficiencies of about 90 per cent could be checked to within 1 or 2 per cent, but efficiencies as low as 10 per cent could hardly be checked within 5 per cent, and the Tyndall apparatus could not determine efficiencies that were less than 5 per cent. Even with these errors the apparatus gives much more accurate determinations than those reported in previous filtering measurements with sugar tubes,[31] mainly because the improved nozzle detailed in Figure 18 permitted better optical comparisons.

Because of the difficulty of accurately observing the filtration, a number of readings of efficiencies were always made. In general, procedure with tobacco smoke was as follows: First, a reading was taken which was known to be greater than the actual efficiency by an amount just perceptible in the Tyndall streams; then a reading, lower than the actual efficiency, was taken in the same way. Five or more pairs of such alternate readings were made, and their average was taken as the efficiency measurement. Table 1 gives some typical results of measurements. The figures show that the percentage differences are small when the filtering efficiencies are high, but increase as the efficiencies become lower.

[31] Fieldner, A. C., Katz, S. H., and Longfellow, E. S., The Sugar Tube Method of Determining Rock Dust in Air: Tech. Paper 278, Bureau of Mines, 1921, 42 pp.

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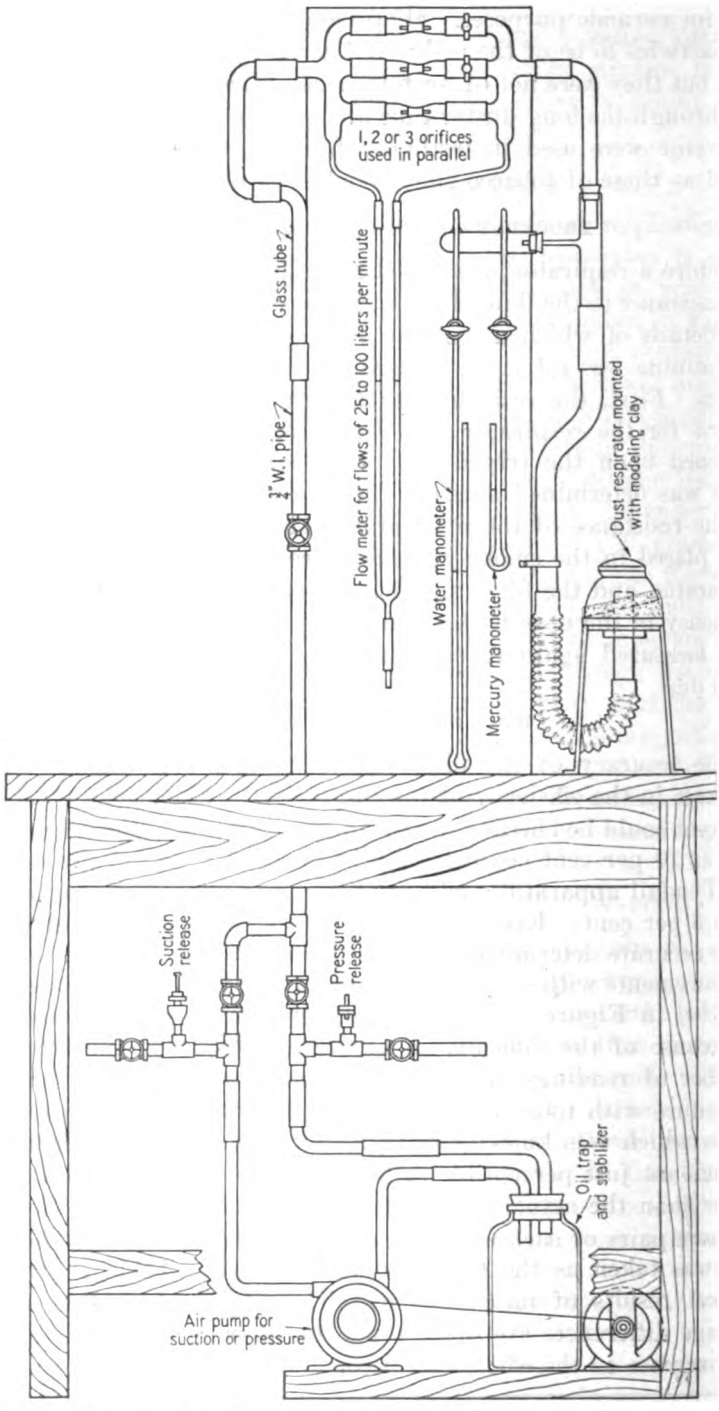
1, 2 or 3 orifices used in parallel
Glass tube
¾" W.I. pipe
Flow meter for flows of 25 to 100 liters per minute
Water manometer
Mercury manometer
Dust respirator mounted with modeling clay
Suction release
Pressure release
Oil trap and stabilizer
Air pump for suction or pressure

FIGURE 19.—Apparatus for measuring resistance of dust respirators to flow of air

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TABLE 1.—*Typical observations of filtering efficiencies against tobacco smoke*

Test No.	Efficiencies		Average
	Excess readings	Insufficient readings	
	Per cent	*Per cent*	
429A	12, 13, 16, 13, 12, 10	6, 4, 8, 6, 10, 6	10
431A	51, 48, 52, 50, 50, 46	42, 35, 46, 40, 48, 43	46
423A	87, 87, 88, 87, 86, 84	84, 86, 84, 86, 82, 83	85
426A	97, 95, 98, 98, 99	96, 96, 96, 96, 98	97

In the data on tobacco-smoke filtration which follow only the averages of percentage observations are reported.

When silica dust was used as the testing medium, the clogging increased the efficiency fairly rapidly; for this reason an attempt was made to match the two dust streams as quickly as possible. The reading of efficiency, when made, was recorded with the time during which dust had come to the filter. In each test a series of efficiencies and time measurements was made to determine the rate of clogging. Sometimes the initial reading was taken as the best determination of the filtering efficiency against silica dust, although it was somewhat higher than the true efficiency. As a rule, when a smooth curve resulted from plotting efficiency against time of testing, the curve was extrapolated to zero time whereat the indicated efficiency was taken as the initial efficiency of the filter against silica dust.

FILTERING EFFICIENCIES OF INDUSTRIAL DUST RESPIRATORS

The respirators mentioned in Tables 2, 3, and 4, and in statements in the text hereafter, are designated by numbers corresponding to the numbers of the figures picturing them. Table 2 is a summary of the construction, facial contact, filter materials, filter thicknesses, filter areas, and weights of the respirators. The thicknesses of filters were determined by measuring with a micrometer while the material was held between two metal plates 1 inch square. The filter areas were determined by direct measurement or by measuring patterns fitted over irregular surfaces; the areas covered by obstructions to the air are not included, however, the filter areas must be taken as approximate. The thickness of paper filters may be increased by including two or more papers; the thinnest filters used in any of the respirators are the single cotton fiber papers 0.02 centimeter thick; the thickest filter is that in the Army gas-mask canister where the absorbent cotton (pressed between wire screens) in two successive filters totals 0.56 centimeter (0.22 inch). Filter areas range from 18.3 to 880 square centimeters. The weights range frome 15 grams (½ ounce) for the lightest respirator to 1,700 grams (3¾ pounds) for the gas mask.

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TABLE 2.—*Comparison of details of respirators*

Respirator No.[1]	Construction										Remarks
	Body material	Facial contact	Exhale valve	Filter							
				Material	Thickness		Area		Weight		
					Cm.	*Inch*	*Sq. cm.*	*Sq. in.*	*Grams*	*Lb. oz.*	
1 (p. 10)	Aluminum	Pneumatic rubber	Mica disk	Sponge	2.0	0.79	29.0	4.3	99	0 3.5	
2 (p. 10)	Rubber	Rubber	Metal disk	do	2.0	.79	30.0	4.6	145	0 5.1	
3 (p. 11)	Rubber and aluminum.	do	None	Paper	.02	.008	35.3	5.5	51	0 1.8	
4 (p. 11)	Aluminum	Pneumatic rubber	Mica disk	do	.12	.05	47.8	7.4	99	0 3.5	Thickness is for 10 sheets together.
5 (p. 12)	do	do	Rubber (flutter)	Felt	.20	.08	18.3	2.84	63	0 2.2	
6 (p. 13)	Felt and rubberized fabric.	Fabric	Rubber disk	do	.6	.25	240.0	37.0	77	0 2.7	Half mask.
7 (p. 14)	Felt and rubber fabric.	Rubber	Rubber (square valve)	do	.6	.25	550.0	85.0	337	0 12	Full mask.
8 (p. 14)	Fabrikoid	Fabrikoid	None	Silk gauze and cheesecloth.	.061	.024	38.1	5.9	15	0 0.5	Thickness represents three-ply cheesecloth and one-ply silk gauze.
9 (p. 15)	Wire screen	Cotton flannel	do	Cotton flannel	.10	.040	142.0	22.0	26	0 0.9	Thickness is two-ply cotton flannel.
10 (p. 15)	Cheesecloth	Cheesecloth	do	Cheesecloth and absorbent cotton.	.19	.074			20	0 0.7	Filtering area is indefinite, but not more than 14 square inches (106 square centimeters).
11 (p. 16)	do	do	do	Cheesecloth	.13	.051			51	0 1.8	Home made; filtering area is indefinite but large; thickness is for six-ply cheesecloth.
12 (p. 17)	Felt	Tissot mask	Rubber (flutter)	Dense woolen felt	.38	.15	880.0	137.0	1,560	3 7	Fogler flat felt filter; weight does not include gas canister of 300 grams, which may be attached; weight of haversack, 440 grams, is included.
13 (p. 18)	Gas-mask canister.	do	do	Absorbent cotton between wire screens.	.56	.22	68.0	10.5	1,700	3 12	Gas mask; thickness is for two filters.

[1] Numbers correspond to the numbers of the figures showing the respective respirators.

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TESTS WITH TOBACCO SMOKE

The tobacco-smoke filtering efficiencies of the respirators and the resistance of the respirators to air flow are given in Table 3. Efficiencies against tobacco smoke range from about 5 per cent or less to 97 per cent for the Fogler flat felt filter. The Army gas-mask canister, type H, had 63 per cent efficiency; this is enough to protect well against the suspensoids commonly met in industry, and to give excellent protection against such ordinary smokes as those arising from fires in coal, wood, paper, and other carbonaceous matter. As a requisite for approval,[32] in accordance with Schedule 14A[33] the Bureau of Mines has adopted a standard filtering efficiency (at a flow of 85 liters per minute) of 50 per cent or more by the tobacco-smoke test in gas masks for protection against smoke. Among the respirators in Table 3 only the Army gas-mask canister and the Fogler flat felt filter can meet this requirement. Some of the others show hardly a 5 per cent efficiency, but even so they are of value in protecting workers from numerous industrial dusts, as is indicated by their being used.

TABLE 3.—*Efficiencies of industrial dust respirators filtering tobacco smoke determined with Tyndall apparatus*

[Rate of air flow, 32 liters per minute]

Respirator number[1]	Filter material	Resistance to flow of air at 85 liters per minute	Number of tests	Efficiencies		Remarks
				Maximum	Minimum	
		Inches of water		*Per cent*	*Per cent*	
1	Sponge	0.7	4	10	7	Wetting sponge had no effect on tobacco smoke.
2	do	.6	8	8	(2)	As much as 220 per cent weight of water added to the sponge increased the resistance to air flow to 1.2 inches of water, without increasing efficiency.
3	Paper	.5	10	15	7	
4	do	.25	1	9	-------	Tested with four-ply tissue filter; eight ply gave 15 per cent efficiency and 0.5 inch of water resistance.
5	Felt	1.3	2	20	19	
6	do	1.5	1	25	-------	
7	do	1.1	1	33	-------	
8	Silk gauze and cheesecloth.	.4	4	(2)	-------	
9	Cotton flannel	.6	3	19	16	
10	Cheesecloth and cotton wool.	.2	1	30	-------	
11	Cheesecloth	.3	1	7	-------	Filtering efficiency is taken from tests of cheesecloth held in flange exposing 100 square centimeters, and tested at rate of 10 liters of air per minute.
12	Dense felt	2.25	1	97	-------	
13	Cotton wool	3.6	2	65	63	Army canister, type H.

[1] Numbers correspond to the numbers of figures showing the respirators. [2] Less than 5.

[32] Fieldner, A. C., Katz, S. H., Frevert, H. W., and Melter, E. G., Gas Mask for Protection in Air Against All Gases, Vapors, and Smokes": Report of Investigations, Serial No. 2719, Bureau of Mines, November, 1925, 10 pp.

[33] Bureau of Mines, Procedure for Establishing a List of Permissible Gas Masks; Fees, character of tests, and conditions under which gas masks will be tested: Schedule 14A, August 25, 1923, 15 pp.

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The multiple tests designated in column 4 of Table 3 were made either with different respirators or by replacing new filters in the same respirators. Sponge filters whether wet or dry showed no advantage over other material in filtering tobacco smoke. However, as a dry sponge unused for a time may shrink and fit the compartment so poorly that there is leakage of unfiltered air around the sponge, it is best to wet the sponge before using the respirator. Sponges differ in texture; a sponge of fine, close texture is best for filtering.

The resistances of the industrial dust respirators were low; the highest was only 1.5 inches of water at an air flow of 85 liters per minute. The Fogler flat felt filter and the gas-mask canister showed 2.25 and 3.6 inches, respectively. The requirements for efficient filtering oppose those for low resistances to air flow, and a balance between the two is necessary when the dimensions of a respirator are fixed.

TESTS WITH SILICA DUST

The efficiencies of dust respirators against silica dust, determined with the Tyndall apparatus, are given in Table 4.

TABLE 4.—*Efficiencies of industrial dust respirators filtering silica dust, determined with Tyndall apparatus*

[Rate of air flow, 32 liters per minute]

Respirator number [1]	Filter material	Resistance to flow of air at 85 liters per minute		Number of tests	Initial efficiency		Highest efficiency after clogging	Time to reach highest efficiency	
		Before test	After test (maximum)		Maximum	Minimum		Minutes	Seconds
		Inches of water	*Inches of water*		*Per cent*	*Per cent*	*Per cent*		
1	Sponge [2]	0.7	1.1	1	9	.....	30	2	0
	do.[3]	.8	1.6	1	22	.....	55	4	0
2	do.[2]	.6	.9	2	17	8	28	3	15
	do.[3]	.8	.9	2	23	9	30	2	30
3	Paper	.5	10.2	4	63	30	100	0	50
4	do	.25	5.2	1	45	.....	100	1	30
5	Felt	1.3	2.8	2	70	70	100	1	20
6	do	1.5	2.2	1	37	.....	100	3	0
7	do	1.1	.....	1	63	.....	100	3	15
8	Silk gauze and cheesecloth	.4	6.1	2	20	10	100	3	30
9	Cotton flannel	.6	6.0	2	61	54	100	5	0
10	Absorbent cotton	.2	.8	1	50	.....	100	3	0
11	Cheesecloth [4]	.3	.6	1	23	.....	23	.....	.....
13	Cotton wool [5]	3.6	6.3	2	99	93	100	0	10

[1] Numbers correspond to the numbers of the figures showing the respective respirators.
[2] Sponge dry.
[3] Sponge wet.
[4] Filtering efficiency is taken from tests of cheesecloth held in flange exposing 100 square centimeters and tested at rate of 10 liters per minute. There was no increase in filtering efficiency during two minutes.
[5] Army canister, type H.

In general, the efficiencies with silica dust are much higher than those given with tobacco smoke; the effect of clogging, which

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causes still higher efficiencies as dust is deposited on the filter, is evident. Even respirator 8, with a filter of 38.1 square centimeters of fine silk gauze and three plies of cheesecloth, became clogged with silica dust until at 3½ minutes the filtering efficiency was 100 per cent. Larger filter areas generally clog more slowly, but this was not always true; for instance, respirators 6 and 7, with larger filter areas of felt, clogged to 100 per cent efficiencies in even less time than respirator 8. This may be due partly to differences in the density of the dust clouds, but the texture of the filter is also a factor. The silk and cheesecloth filter respirator, No. 8, showed 6.1 inches resistance when clogged to 100 per cent efficiency, whereas the larger area of felt in respirator 6 had only 2.2 inches resistance under the same condition.

The paper filters clogged to 100 per cent efficiencies quickly, and developed high resistance to flow.

The effect of texture is well demonstrated by the sponge-filter respirators 1 and 2. One of these respirators has a body of aluminum and the other has a body of rubber; otherwise they are nearly alike, and the different filtering results are due almost wholly to the different sponges. The better sponge when dry showed an initial efficiency of 9 per cent, which increased to a maximum of 30 per cent. When the sponge was wet the efficiency started about at 22 per cent and increased to 55 per cent. The inability of these sponges to clog to a higher efficiency than 55 per cent must be due to their containing some relatively large channels which allow the dusty air to pass without filtering. Wetting the sponges materially increased their effectiveness against the silica dust.

COMPARISON OF FILTERING EFFICIENCIES OF FABRICS

The tests of the dust respirators described are not well suited for showing the inherent filtering qualities of the filter materials, because no two of the respirators expose the same areas of filter, and structural differences also may influence the test results. In order to compare the filtering qualities of the papers and fabrics better, other tests were made by exposing 100 square centimeters of each material to the smoke or dust clouds in the Tyndall apparatus. A special holder called a "flange" was used; it is shown in Figure 20.

The flange consists of two metal funnels soldered at their large circumference to large, flat metal rings, bolted together so as to clamp the filter material between them and expose exactly 100 square centimeters to passage of the air and smoke. Several plies of paper or fabrics cut in circles may be clamped together. Weak materials that might break by the air pressure on one side or materials that

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bow out were backed by a circle of fly screen. The fabric edges were sealed with paraffin to hold multiple layers together and prevent leakage of air or smoke from the apparatus. An air flow of 10 liters per minute was used for these tests. Table 5 gives the fabrics and materials tested in the flange and the test results against tobacco smoke and silica dust.

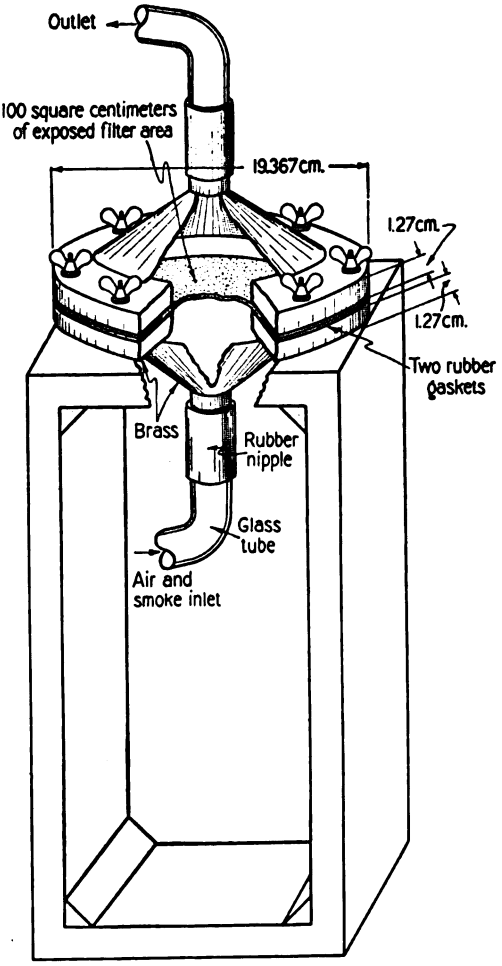

FIGURE 20.—Flange for holding fabrics so as to expose an area of 100 square centimeters for filtering tests

EFFECT OF INCREASING PLIES OF FABRIC IN FILTER

Figure 21 presents graphically the increasing filtering efficiencies against tobacco smoke of four fabrics, absorbent cotton, and a filter paper, each tested in multiple layers, increasing to as many as 30 plies for cheesecloth. Figure 22 similarly gives the filtering efficiencies of these materials against silica dust. To avoid the effects of clogging, these efficiencies against the dust were determined as soon as possible after filtering started. Filtering efficiencies against both tobacco smoke and silica dust increase with the number of layers of each fabric, but each succeeding layer causes a smaller increase than the ones before it.

The graphs of Figure 23 show plies of fabric as the abscissas on a linear scale, and the expression, $\frac{100-\text{percentage efficiency}}{100}$, as the ordinates on a logarithmic scale; separate graphs are shown for each fabric. The data yielded by the tests of multiple ply filters

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are plotted on the graphs, and the straight lines drawn thereon show the general trend of the plotted points. The data falling along the straight lines indicate that each layer in a multiple ply filter devel-

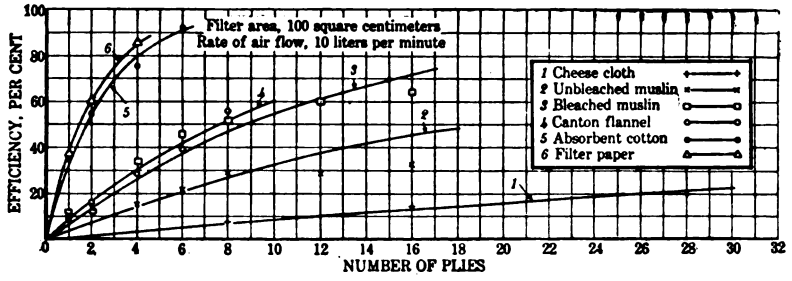

FIGURE 21.—Increased filtering efficiencies of fabric filters against tobacco smoke as the number of plies of fabric are increased

ops about the same efficiency as every other layer—that is, each layer of fabric in a filter removes apparently the same proportion of the smoke or dust which penetrates to it—and the concentration of

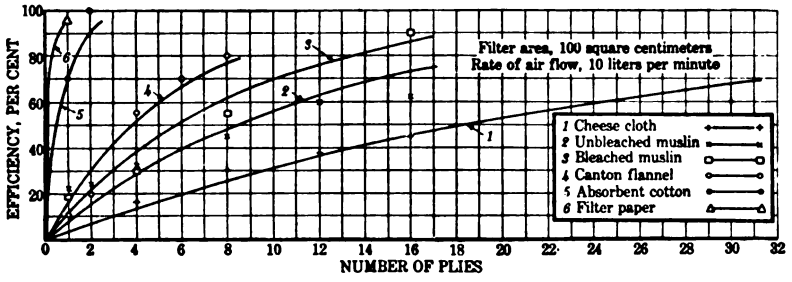

FIGURE 22.—Increased filtering efficiencies of fabric filters against silica dust with increasing plies of various fabrics. The efficiencies were determined as quickly as possible to avoid effect of the clogging caused by deposited dust

the dust does not affect the respective filter actions. (These effects must be stated as "apparent," as the smoke and dust retained by each layer were not determined separately.)

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TABLE 5.—*Fabrics used as filters and their filtering efficiencies against tobacco smoke and silica dust in air*

[Filter area, 100 square centimeters; rate of air flow, 10 liters per minute]

Material	Description	Thickness (nominal)		Number of plies of fabric in filter	Tobacco smoke tests, filtering efficiency	Silica dust tests				Resistance of filter and flange to flow of air at 85 liters per minute	
						Filtering efficiency		Duration			
		Centimeter	Inch			Initial	Final	Minutes	Seconds	Before testing	After silica dust test
					Per cent	*Per cent*	*Per cent*			*Inches of water*	*Inches of water*
Cheesecloth	30 by 30 threads per square inch			4		17				0.2	0.6
				8	9	30				.3	.6
				12		38					.6
				16	14	45	45	2	00	.4	.6
				28	20					.4	
				30		60	60	2	00	.7	.8
Canton flannel	Flannel nap placed toward dust, 45 by 75 threads per square inch, 6.35 ounces per square yard.			1	9	10	100	2	10	.6	2.4
				2	16	20	100	1	30	.8	2.2
				4	29	55	100	1	45	1.4	2.7
	Dust suspension was lighter than preceding tests			6	39	70	95	6	30	1.8	2.3
				8	56	80	100	2	15	2.2	3.0
Muslin, unbleached	60 by 60 threads per square inch, 3.85 ounces per square yard			1	9	22	40	2	00	.4	1.6
				2	15	24	100	4	00	.6	2.5
				4	16	32	100	2	40	.8	2.9
				6	22					.8	
				8	29	45	100	2	35	1.0	2.9
				12	29	50	100	0	50	1.2	2.9
				16	33	62	100	3	5	1.5	2.7
Muslin, bleached	85 by 85 threads per square inch, 3.85 ounces per square yard			1	12	19	100	1	20	.8	4.0
				2	13					1.1	
				4	34	80	100	2	00	2.2	4.0
				6	46					2.6	
				8	52	55	100	1	30	3.3	6.0
				12	60					5.2	
				16	64	90	100	0	15	6.3	11.5

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Felt	Felt for making pennants, cotton and wool	0.099	0.039	1		46	100	1	10	.6	3.3
	Cotton and wool, Western Felt Co., No. 108/8	.122	.048	1	30	50	85	3	00	.5	.6
	Cotton and wool, Western Felt Co., No. 108	.135	.053	1	28	65	100	3	00	.5	.8
	Cotton and wool, Western Felt Co., No. 108/10	.147	.058	1	33	65	90	4	00	.6	.6
	Cotton and wool, Western Felt Co., No. 4076	.173	.068	1	33	55	100	1	45	.6	1.3
	Cotton and wool, Western Felt Co., No. 112	.224	.088	1	50	85	85	3	00	.6	.6
	Cotton and wool, unknown origin	.305	.120	1		57	100	6	00	.7	3.6
	Harness makers' felt, cotton and wool	.505	.199	1	46	77	100	3	30	.8	3.7
	Special dense wool felt, from Fogler flat felt filter. Several separate tests gave efficiencies with tobacco smoke at 80 to 90 per cent and with silica dust 92 to 96 per cent.	.381	.15	1	86	94	100	0	30	5.2	6.2
Filter paper	Paper made of cotton fiber	.025	.010	1	10	57	100	1	30	.5	1.0
	----do	.089	.035	1	50	85	100	1	15	.6	3.1
	----do	.094	.037	1	45	75	100	1	45	.6	1.3
	Chemical filter paper, inexpensive grade, S. & S. No. 595	.015	.006	1		100	100	0	5	5.1	15.3
	Chemical filter paper, high grade, for rapid filtering, S. & S. Black label, No. 589.	.020	.008	1	38	96	100	0	30	2.1	7.8
	----do			2	60					3.4	
	----do			4	86					6.8	
	Chemical filter paper, high grade, for retaining very small particles, S. &. S. No. 589, blue label.	.018	.007	1	96	100	100	0	5	16.3	24.5
	Chemical filter paper, hardened, S. & S. No. 575	.010	.004	1	95					50.0	
Absorbent cotton	Made for medicinal purposes; a piece cut 100 square centimeters area weighed 2.134 grams, equivalent to 6.30 ounces per square yard. Thickness was about one-half inch (1.3 centimeters) in naturally fluffy condition.	.183	.072	1	35	75	100	5	00	.15	.25
				2	55	100	100	2	30	.25	.35
				4	75					.80	
				6	92					1.60	

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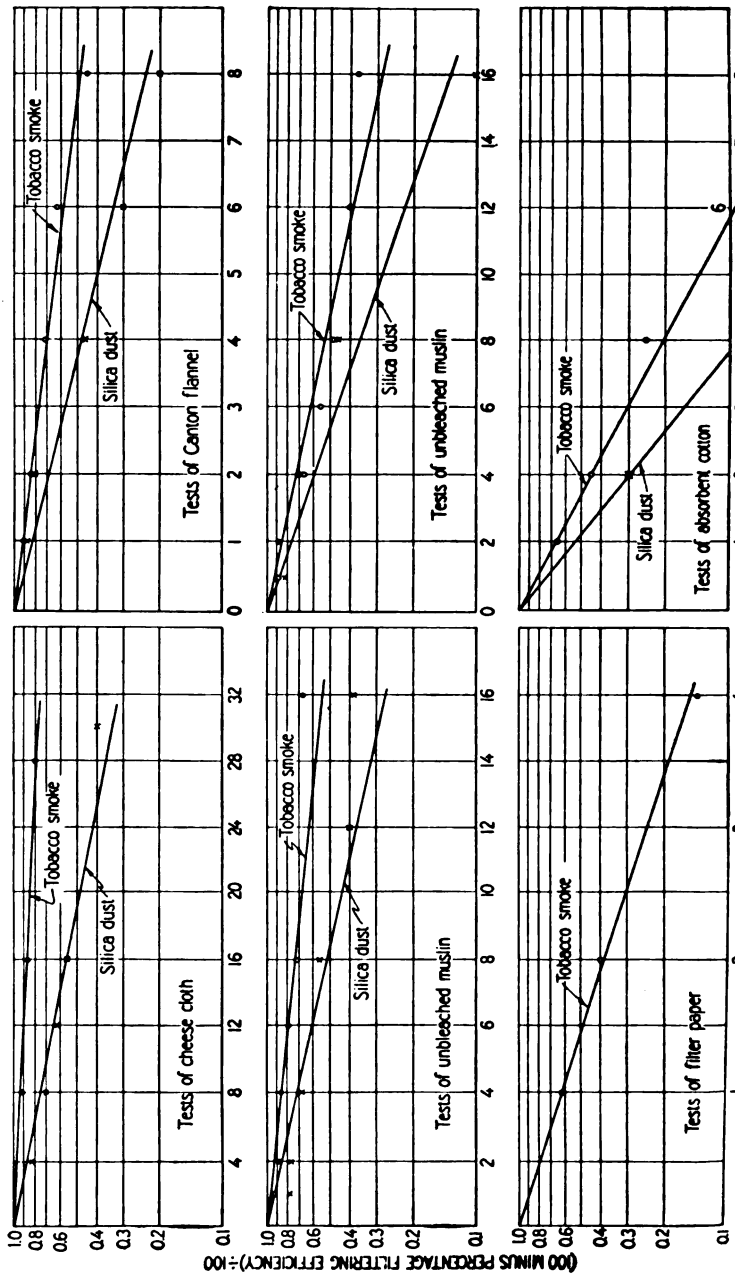

FIGURE 23.—Charts showing that each ply of fabric in multiple ply filters retains about the same proportion of the smoke or dust that penetrates to it

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TABLE 6.—*Comparison of filtering efficiencies of multiple ply filters determined by experiment with the computed efficiencies*[1]

Filter material	Number of plies	Filtering efficiencies			
		Against tobacco smoke		Against silica dust	
		Determined	Calculated	Determined	Calculated
		Per cent	*Per cent*	*Per cent*	*Per cent*
Cheesecloth	4			17	14
	8	9	7	30	25
	12			38	35
	16	14	13	45	44
	28	20	22		
	30			60	66
Canton flannel	1	9	9	10	17
	2	16	17	20	31
	4	29	31	55	52
	6	39	42	70	67
	8	56	52	80	77
Muslin, unbleached	1	9	4	22	8
	2	15	7	24	15
	4	16	14	32	28
	6	22	21		
	8	29	27	45	48
	12	29	37	60	63
	16	33	46	62	73
Muslin, bleached	1	12	7	19	12
	2	13	14		
	4	34	25	30	39
	6	46	36		
	8	52	44	55	63
	12	60	59		
	16	64	69	90	87
Filter paper	1	38	38	96	96
	2	60	61		
	4	86	85		
Absorbent cotton	1	35	33	70	70
	2	55	55	100	91
	3				
	4	75	80		
	6	92	91		
	8	97	96		
	10	99	98		

[1] Efficiencies computed by means of the equation $\frac{1}{p}\log(1-E_p)=\log(1-e)$ and the position of the graphs of the equation on Figure 23. p=number of plies; e=efficiency (expressed as decimal fraction) of a filter of one ply; E_p=efficiency of a filter of p plies. Measurements of efficiencies were made with filters of 100 square centimeter areas and air flow of 10 liters per minute, by means of the Tyndall apparatus.

The relations between the filtering efficiencies and the number of plies in a filter, outlined in the preceding paragraphs, may be stated mathematically by means of the expression:

$$\frac{1}{p}\log(1-E_p)=\log(1-e)=K, \qquad (1)$$

where e=filtering efficiency of a single ply expressed as a decimal fraction,

p=the number of plies of fabric included in a filter,

E_p=filtering efficiency of a filter composed of p plies of fabric, and

K=a constant for each kind of filter.

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A simpler equation which is equivalent to equation (1) may also be used:

$$Q=q^p \qquad (2)$$

where Q=proportion of dust passing a filter,
p=number of plies in filter, and
q=proportion passing a single ply filter.

The straight-line graphs in Figure 23 represent equation (1) and the curves in Figures 21 and 22 correspond; by means of the equation and the positions of the graphs the filtering efficiencies of various multiple ply filters may be calculated. These calculated efficiencies and the corresponding efficiencies found in testing are compared in Table 6. In general, the agreement is fairly satisfactory, in view of the irregularities of fabrics, the difficulty of accurate comparisons of the smoke streams in the Tyndall apparatus, and the tendency of filters to clog with silica dust. It may be said, therefore, that equation (1) gives with fair accuracy the relations between the filtering efficiencies of fabric filters in the various multiple layers.

CAUSE OF HIGHER EFFICIENCIES OF FILTERS WITH FEWER PLIES

In Table 6 it will be noticed that, with three exceptions, the determined efficiencies of the filters with the least number of plies are somewhat higher than the calculated efficiencies. The reasons for the determined efficiency being higher may be (1) variations in the size of the suspended particles; and (2) electrical charges on the particles.

VARIATION IN SIZE OF PARTICLES

If the particles are not of a uniform size, the larger ones will be most easily caught and retained by a filter, regardless of whether the filtering effect of a fabric is due to straining the air through holes too small for the suspended particles to pass, or whether it is due to precipitating the particles upon the surfaces of the minute, tortuous channels, through the filter, each channel being larger in cross sectional area than a particle retained therein. Undoubtedly, both of these actions play a part in the filtering action of the fabrics described. That particles of the silica dust differ in size is certain; therefore the first filters of a series tend to remove more readily the larger particles and some of the smaller ones, and permit mostly the less easily retained small particles to penetrate to succeeding filters. Differences in the size of the particles are responsible in part, therefore, for some of the apparent lesser efficiencies of the subsequent filter layers.

ELECTRICAL CHARGES ON PARTICLES

The diameter of the tobacco-smoke particles varies by 1.8 per cent from the mean, as shown by Wells and Gerke.[34] This variation is

[34] Wells, P. V., and Gerke, R. H., "An oscillation method for measuring the size of ultramicroscopic particles": Jour. Am. Chem. Soc., vol. 4, 1919, pp. 312–329.

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too small to account for the decreased filtering efficiencies of the successive plies against tobacco smoke; but the second factor, that of electrical charges on particles, may cause a considerable effect with tobacco smoke; this effect, furthermore, is not absent with silica dust. That the tobacco-smoke particles and the silica particles suspended in air had electrical charges was demonstrated by microscopic examination in an ultracondenser cell [35] and within an electric field. Both the tobacco smoke and the silica dust showed a considerable proportion of particles charged, some positively and some negatively, as well as some uncharged particles.

SUMMARY

In view of the nonuniformity of particle sizes and of their electrical charges, the relations between the numbers of plies in multiple filters and their combined filter efficiencies may be summarized as follows:

1. The experiments indicate that in the filtration of tobacco smoke or air-floated silica dust the efficiencies of filters increase with the number of plies; each ply removes (in effect) practically the same proportion of the smoke or dust that penetrates to it, regardless of the concentration of the dust.

2. In the experiments made, the foremost filters in a series tended to show somewhat greater efficiencies because they removed the more easily retained particles, those of larger size and those bearing electric charges.

3. It appears that filters of multiple ply fabrics, when filtering suspended particles that are of uniform size and are electrically neutral, will show combined efficiencies compared to the efficiency of a single ply fabric, according to equation (1). The filters tested against tobacco smoke and silica dust showed a fair agreement with the equation, although some of the particles had electric charges and the silica particles were not exactly uniform in size.

EFFECT OF DEPOSITED SMOKE AND DUST ON THE ACTION OF THE FILTER

The filtering efficiencies given in Table 5 are those determined before changes occurred through deposits of smoke or dust on the filters. Tobacco smoke has virtually no tendency to clog a filter, and as a rule there is no change in filtering efficiency or resistance to air flow when the smoke is caught upon the filter. Determinations of efficiency may thus be checked by consecutive measurements with the same filter. Some filter materials, notably canton flannel,

[35] Jentzsch, F., ["Dark-field illumination"]: Verhand. Deut. phys. Gesell., Bd. 12, 1910, pp. 975–991; Science Abst., vol. 14, 1911, p. 16.

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showed a decrease in efficiency later if the smoke was not dried, because enough moisture was deposited upon the fabric to draw the fibers of the nap together.

Fabrics filtering silica dust increased in efficiency from the start as dust was deposited upon them, and their resistance to air flow increased simultaneously. It was necessary to determine the initial efficiencies as soon as possible in order to find the approximate efficiencies of the fabric without much increase from deposited dust; as a rule, this could be done in less than half a minute. Thereafter the efficiencies and the time were noted until 100 per cent was attained. When the data indicated a smooth curve of efficiency against time, the curve was extrapolated to zero time to give the initial efficiency, and this was taken as the filtering efficiency of the fabric alone. Figure 24 presents three typical graphs of the efficiency of fabrics filtering silica dust. In test 506 the initial effi-

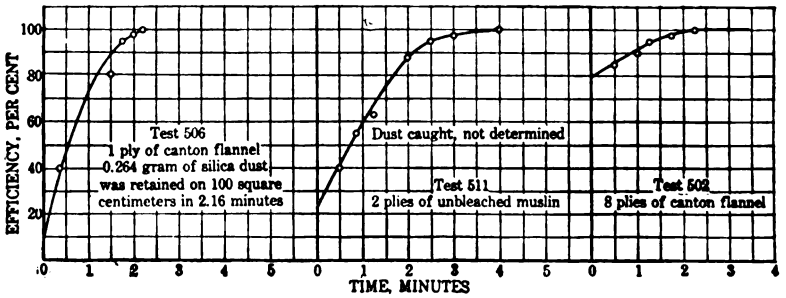

FIGURE 24.—Increased filtering efficiencies of three fabrics as silica dust was deposited upon them

ciency is taken as 10 per cent, in test 511 as 24 per cent, and in test 502 as 80 per cent.

When the dust clouds were very dense the clogging was more rapid, as in test 506 of Figure 24. In this test the amount of dust retained on the filter was determined by ignition and weighing; 0.264 gram of silica dust was retained on 100 square centimeters in 2.16 minutes of testing. This result indicates that a deposit of 2.64 milligrams of dust per square centimeter of fabric increased its efficiency from 24 to 100 per cent, or about fourfold. The resistance to air flow at 85 liters per minute before the dust was deposited was 0.8 inch of water; after the dust had increased the efficiency to 100 per cent the resistance had increased threefold to 2.4 inches of water. By integrating the area under the curve, the air flow being taken as 10 liters per minute and the particles assumed to be of uniform size (not exactly true), a dust concentration of 2.3 grams per cubic meter is indicated. This is approximately the maximum concentration developed in testing, and is about 100 times dustier than dusty air

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in which men may work. Hence, the clogging of a fabric in actual service as a respirator filter would be very much slower.

RESISTANCE OF FABRIC FILTERS TO THE FLOW OF AIR

The resistance of the filters to air flow increases in proportion to the number of plies of included fabric, as is shown by the straight-

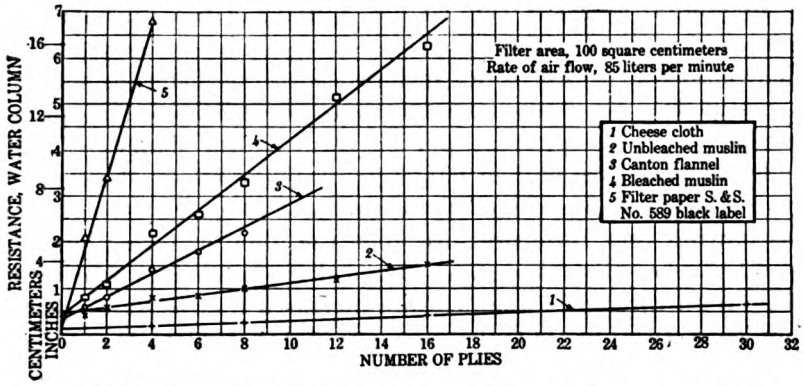

FIGURE 25.—Increased resistance of filters as layers of fabric are increased

line graphs in Figure 25. The determined points are those listed in Table 5, which were for fabrics clamped in the flange. The lines do not start from the point of zero resistance with zero plies of fabric in the flange, possibly in part because of the turbulence of the air approaching and leaving the pores on the incoming and outgoing sides of the filters; it is not due to the resistance of the flange alone,

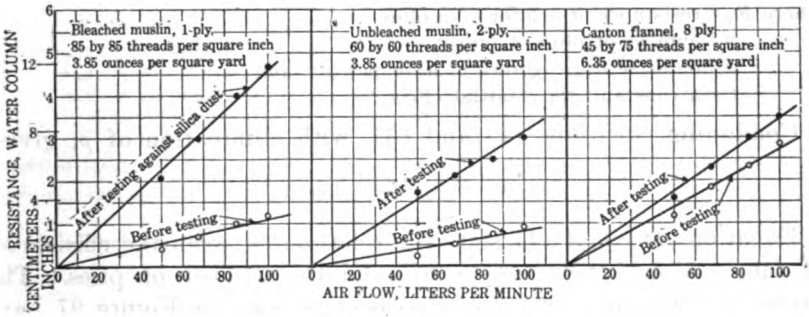
Bleached muslin, 1-ply
85 by 85 threads per square inch
3.85 ounces per square yard
Unbleached muslin, 2-ply
60 by 60 threads per square inch
3.85 ounces per square yard
Canton flannel, 8 ply
45 by 75 threads per square inch
6.35 ounces per square yard
After testing against silica dust
Before testing
RESISTANCE, WATER COLUMN
CENTIMETERS
INCHES
AIR FLOW, LITERS PER MINUTE

FIGURE 26.—Resistance of three filters to air flowing at various rates, before and after testing against silica dust

because the resistance of the flange was found to be negligible (0.03 inch of water at an air flow of 85 liters per minute) when it was tested without an included fabric. These "initial effects" on resistance are not excessive, as they are only 0.1 to 0.45 inch of water, but they are included in the succeeding calculations involving resistance.

Figure 26 shows the resistance of three fabrics at rates of air flow of 50, 67.5, 84, and 100 liters per minute. The higher resistances,

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determined after testing against silica dust, were taken immediately after the filtering efficiencies had increased to 100 per cent. This increase was least for canton flannel. The data show a slight tendency toward convexity to the axis of the abscissa, but the straight-line graphs shown are accurate enough for practical purposes. The straight lines indicate that resistance is very nearly proportional to the air flow, as is true in general for capillary orifices; in fact, every filter appears simply as an assembly of numerous capillary passages.

The absorbent cotton is not included with the materials shown in Figure 25, because its resistance was altered with increasing plies in consequence of the pressure put on them by the flange. When a single ply was present, the flange gripped the edges of the cotton between a lower support of fly screen and a cover of cheesecloth, thus putting very little pressure upon the filter surfaces; but when several plies of the cotton were included the pressure was considerable. With three plies the pressure increased the resistance per ply more than twofold, but the pressure did not alter the filtering efficiencies noticeably.

COMPARISON OF EFFICIENCIES OF FABRIC FILTERS WITH THEIR RESISTANCES TO FLOW OF AIR

Equation (1), $\log (1-E_p)=p \log (1-e)$, stated the filtering efficiencies of any number of plies of fabric. The resistances of the filters as indicated by the graphs on Figure 25 may be expressed thus:

$$R_p=pr+C, \tag{3}$$

where R_p=resistance of a filter of p plies,
p=number of plies of fabric,
r=increase in resistance of filter per ply, and
C=a constant, the "initial effect."

Combining equations (1) and (3), with elimination of p, gives:

$$\log (1-E_p)=\frac{R_p-C}{r} \log (1-e) \tag{4}$$

Equations (3) and (4) state the relations between the efficiencies of fabric filters, their resistances, and the number of plies. The curves (except the curve for absorbent cotton) in Figure 27 have been drawn according to equation (4), and show those relations graphically. The curves for absorbent cotton are not in accord with equation (4), because of the variable resistances caused by compression. The data used in calculating the curves were from tests of filters 100 square centimeters in area, their efficiencies determined at air flow of 10 liters per minute, and their resistances at 85 liters per minute. At any other rate of air flow, the resistances will change as the ratios of the flows change. The broken portions of the curves are extrapolations beyond the experimental data.

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Figure 27 shows great differences in the filtering qualities of the various materials in filters of equal resistances. For instance, if a resistance of 1 inch of water at a flow of 85 liters per minute

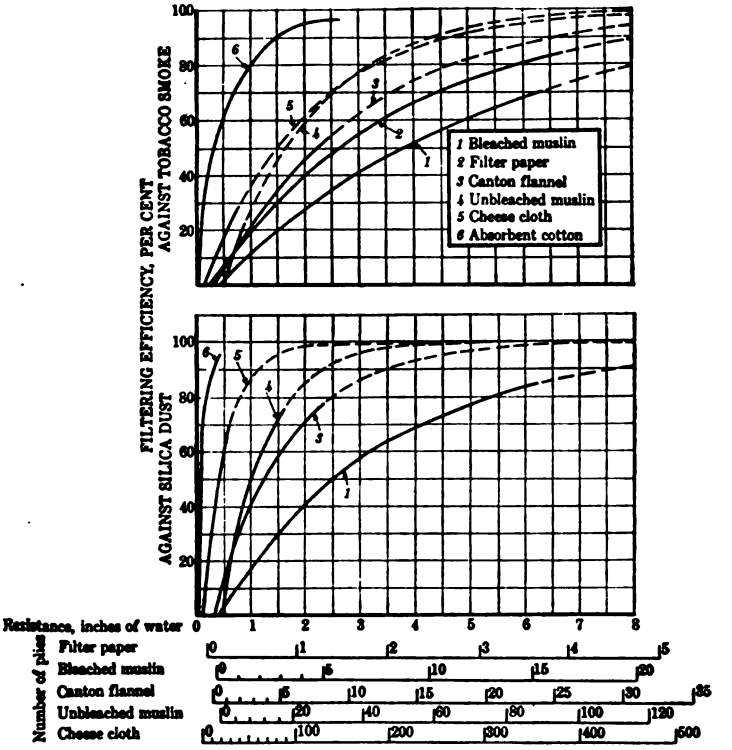

FIGURE 27.—Filtering efficiencies of multiple ply fabric filters with their resistances to flow of air. Area of filters was 100 square centimeters; rate of air flow in determining filtering efficiencies, 10 liters per minute; in determining resistance, 85 liters per minute

is permitted, a filter may be chosen with any of the following characteristics:

Characteristics of filters for a predetermined resistance and rate of filtration

Material	Number of plies	Efficiency against silica dust (100 sq. cm. area of filter, 10 liters per minute air flow)
		Per cent
Bleached muslin	2	18
Canton flannel	3	39
Unbleached muslin	7	72
Cheesecloth	52	86
Absorbent cotton		+90

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If, on the other hand, a filtering efficiency of 50 per cent against tobacco smoke is required (100 square centimeters area of filter, 10 liters per minute air flow), it may be obtained from filters having these characteristics:

Characteristics of filters for a predetermined efficiency and rate of filtration

Material	Number of plies	Resistance to flow of air at 85 liters per minute
		Inches of water
Bleached muslin	8	3.75
Canton flannel	7	2.2
Unbleached muslin	18	1.6
Cheesecloth	80	1.5
Absorbent cotton		.3

The filter paper will give an efficiency of 38 per cent for one ply or of 60 per cent for two plies; an efficiency of exactly 50 per cent could not be obtained unless one sheet of regular thickness and one thinner sheet of paper were used. Any of the fabric filters might be made, but actually the canton flannel or the unbleached muslin would be selected because they would have lower resistance than the bleached muslin, and construction would be easier with 7 or 18 plies as compared with 80 plies of cheesecloth. Filters of absorbent cotton could be made durable by quilting the cotton between two plies of fabric. These filters should combine high efficiency with very low resistance, provided the cotton is not compressed too much.

FILTERING EFFICIENCIES AT DIFFERENT RATES OF AIR FLOW

A gas-mask canister containing two filters of absorbent cotton was tested for filtering efficiency against tobacco smoke at rates of air flow of 10, 32, and 85 liters per minute, and gave corresponding efficiencies of 88, 80, and 70 per cent. Respirator 10, tested at 32 and 85 liters per minute, gave efficiencies of 30 and 20 per cent, respectively, against tobacco smoke. In general, then, it may be said that the efficiencies of the filters decrease with the increase in the rate of air flow. The changes in the filtering efficiencies throughout the ordinary breathing rates, which range from about 10 to 32 liters per minute, are not important.

PROPERTIES OF FILTERS AND DESIGN OF DUST RESPIRATORS

It has been shown that an efficient filter for air-borne dust particles, even those as small as tobacco-smoke particles 0.27 micron in diameter, can be made from a sufficient number of plies of any of the fabrics. Tightly woven material is not necessary, because very

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loosely woven materials like cheesecloth can be made into efficient filters if enough plies be superimposed. Cotton wool alone makes a most efficient filter, and shows that a multitude of air passages between minute fibers is conducive to efficient filtration with minimum resistance.

The resistance of the filters to the flow of air through them is a highly important factor in the design of dust respirators, because respirators having a resistance greater than 4 inches of water when the rate of air flow is 85 liters per minute are impractical. They will not be worn, even for short periods, because they necessitate too much exertion in breathing. Respirators with resistances of 2 to 4 inches may be worn, but after about half an hour the wearer must rest or exert himself less. The resistance of filters in dust respirators intended for continuous working use should not exceed 2 inches of water, and preferably should be less than 1 inch. These limitations on the resistance of filters restrict filtering efficiencies, so in a practicable respirator it is necessary to strike a balance between the filter resistance and the filtering efficiency that may be obtained.

The area of respirator filters should be made as large as is practicable, because the increased area reduces the rate of air flow per unit of area and thereby tends to increase the filtering efficiency and decreases the resistance.

COMPARISON OF CLOGGING OF RESPIRATOR FABRICS

Tightly woven fabrics of hard-twisted thread clog more readily than softer materials; a cheesecloth filter shows little tendency to clog, but it must be made of many layers to be efficient; canton flannel, with the nap toward the dusty air, does not clog very readily, and with the same number of plies makes a much better filter than cheesecloth. Felts and papers clog more readily than filters of loosely woven fabrics or absorbent cotton loosely held. Woolen filter materials have been tried, but they show no advantage over cotton materials.

NEW TYPE OF DUST RESPIRATOR

A dust respirator embodying the principles outlined was designed by the authors of this paper. Figures 28 and 29 give the details of construction. This respirator consists of a filter built into a square brimless hat or cap, and a nose cap or cover which connects with the cap by means of a rubber tube. The inspired air passes first through the outer filtering material to the interior of the cap, then through a check valve on the top center, and through the tube to the nose cap.

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In order to avoid the discomfort caused when the face is covered, the part covering the face has been reduced to a minimum; it consists only of the small nose cap molded of rubber with the edges flanged to give a broad contact with the skin. The mouth is uncovered, so that the wearer may talk freely or expectorate; freedom in these respects, according to many published statements, is desired by most workmen. A very large canton-flannel filter surface is pro-

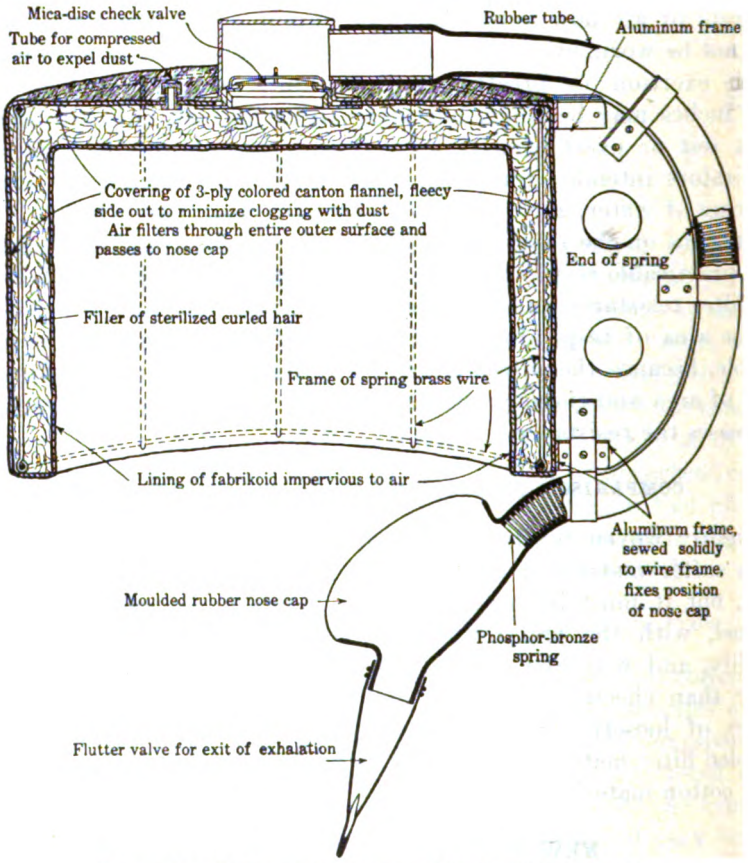
Mica-disc check valve
Tube for compressed air to expel dust
Rubber tube
Aluminum frame
Covering of 3-ply colored canton flannel, fleecy side out to minimize clogging with dust
Air filters through entire outer surface and passes to nose cap
End of spring
Filler of sterilized curled hair
Frame of spring brass wire
Lining of fabrikoid impervious to air
Aluminum frame, sewed solidly to wire frame, fixes position of nose cap
Moulded rubber nose cap
Phosphor-bronze spring
Flutter valve for exit of exhalation

FIGURE 28.—Detail of the Bureau of Mines dust respirator

vided, fashioned into the cap for the head. The filter area is about 217 square inches (1,400 square centimeters), or 60 per cent greater than in the Fogler flat felt filter, which has the largest filter area of any of the respirators described. The rubber tube contains a spiral spring, and is bound to the frame of the respirator in such a way that when the respirator is adjusted upon the head the nose cap is fixed in proper position. There was no leakage between the nose cap and the face with 90 per cent of the persons who tried the

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respirator; the 10 per cent who were not fitted required a different form of nose cap. The mica-disk type of check valve prevents back flow of exhaled air, and causes the exhalations to pass out through a flutter valve of rubber at the lower side of the nose cap. There is practically no dead space and air is not rebreathed.

FILTER

The cap filter is built on a wire frame which is lined with pyroxylin fabrikoid, impervious to air, to prevent dusty air being drawn over the wearer's scalp and hair. Three sizes—small, medium, and large—are required for heads of different sizes. The Canton flannel is placed with its fleecy side outward. This material was chosen because its tendency to clog with deposited dust is less than that of most other materials, and because an efficient filter can be constructed from a few thicknesses. Between the inner lining and the outer filter is a filler about 1 inch thick of sterilized curled hair like that used by upholsterers. This filler keeps the filter fabric and pyroxylin fabric apart, is light, and allows air to pass with minimum resistance from all parts of the filter to the exit valve. The entire respirator weighs 21 or 22 ounces (600 to 625 grams); this is only about one-third the weight of the Army gas mask and canister, which the new respirator nearly equals in filtering efficiency. The weight is balanced on the head and is not oppressive, because the head is free to move in any direction.

FIGURE 29.—Bureau of Mines dust respirator designed for low resistance and high filtering efficiency

Vision is unobstructed except that in side glances of about 45° the tube interferes with sight by one eye.

EFFICIENCY

Tested at an air flow of 85 liters per minute, a respirator, made with a filter covering of three plies of Canton flannel, proved 58 per cent efficient against tobacco smoke and 93 per cent against

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silica dust; at a 32-liter rate the respirator was 70 per cent efficient against the smoke. The resistance to air flow at 85 liters per minute was 1.2 inches of water; after 10 minutes testing against silica dust in the Tyndall apparatus, the resistance had increased only about 1 inch. Another respirator with a two-ply Canton-flannel covering gave an efficiency of 42 per cent against tobacco smoke and a resistance of 0.8 inch of water.

A hose connection for blowing out accumulated dust by means of compressed air is provided near the mica-disk valve. About 15 pounds pressure is desirable.

To clean and sterilize it, the fabrikoid and rubber nose cap may be washed with a 2 per cent lysol solution. It is best not to wet the filter material, but the entire respirator may be sterilized in an atmosphere of formaldehyde or sulphur dioxide.

Only a few of these respirators have been made experimentally in the laboratory; but two were tried over a year in the sampling room of the Pittsburgh experiment station of the Bureau of Mines, where considerable dust from coal, shale, ashes, and minerals arises during grinding and screening operations. The wearers considered the cap respirators very efficient in preventing inhalation of dust, and found them comfortable.

Should the respirators be worn by miners in dusty workings, the thick head covering would also serve to prevent injury to the head from falls of rock.

SUMMARY AND CONCLUSIONS

1. This paper describes representative types of dust respirators used in industry and presents the results of laboratory tests to determine their filtering efficiencies and resistances to air flow.

2. The efficiencies of the industrial dust respirators in restraining tobacco smoke range from 5 to 33 per cent when the air is passed at a rate of 32 liters per minute; a gas-mask canister with two filters of absorbent cotton showed 63 per cent efficiency. The Fogler flat felt filter was most efficient, showing 97 per cent.

3. The efficiencies against silica dust floated in air range from about 9 to 70 per cent for the dust respirators, or about twice the efficiency against the tobacco smoke; most of the silica particles were 1 micron in diameter or four times the diameter of the tobacco-smoke particles.

4. As the dust most injurious to miners, stone workers, and many others engaged in dusty trades are about 1 micron in diameter the respirators, if worn, can prevent a considerable amount of dust, but not all of it, from being inhaled.

5. Although the laboratory study has shown that most dust respirators are not highly efficient in removing tobacco smoke (very difficult

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to arrest) from air, a filter that removes 50 per cent of the tobacco smoke from air flowing at rate of 85 liters per minute is very efficient in restraining the ordinary dusts encountered in industry and also the smokes, such as those from burning wood or other carbonaceous material, that city firemen encounter. Hence, the Bureau of Mines adopted a 50 per cent efficiency against tobacco smoke by the laboratory tests as a standard requirement, besides other requirements, for the approval of respirators or gas masks to afford protection from smoke or dust.

6. As the laboratory tests of the dust respirators were severe, the low efficiencies given do not indicate the general efficiencies of these respirators under all industrial conditions. Much of the dust encountered in industry is less difficult to arrest, and the over-all efficiency of the respirators in actual service is correspondingly higher. The tests thus show that as a rule the respirators are of much value in removing injurious dust from inspired air.

7. The discomfort caused by respirators covering the face—the heat engendered thereby, the irritation of the skin at contact with the respirators, and the resistance to the flow of the air breathed—are the most serious disadvantages of respirators. The resistances of industrial dust respirators to air flowing at 85 liters per minute were 0.25 to 1.5 inches of water. The Fogler flat felt filter had a resistance of 2.25 inches and the gas-mask canister 3.6 inches.

8. A man wearing a gas mask can work hard only about half an hour; then the extra effort caused by the resistance to breathing compels him to stop to rest or greatly reduce his exertion. The resistance of the dust respirators, although it causes some discomfort, does not seriously interfere with a man's exertions until the filter becomes clogged with deposited dust and the resistance correspondingly increased. The filter must then be cleaned or freed of dust, or it must be replaced by a fresh one.

9. Filters of various fabrics, including cheesecloth, canton flannel, unbleached muslin, closely woven bleached muslin, filter paper, and absorbent cotton, all made for test purposes so as to expose exactly 100 square centimeters of filter area, were tested against tobacco smoke and against silica dust in air flowing at a rate of 10 liters per minute. Each material was tested in a single layer and in multiple layers. Results showed that each layer of fabric (in effect) removes about the same proportion of smoke or dust that penetrates to it before the filters become clogged or altered by deposits of an arrested material, such as silica dust. Consequently, when the efficiency of a single ply of a filter is known, the efficiency of any multiple ply filter of that material may be calculated.

10. Silica dust clogged filters rapidly and increased the resistance to air flow, but some materials were more resistant to clogging than

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others. The dense filters of paper or closely woven muslin clogged most rapidly; filters of loose texture like cheesecloth or absorbent cotton clogged the least.

11. The efficiencies of the filters were increased by clogging with dust until eventually many filters gave an efficiency of 100 per cent.

12. Tobacco smoke did not clog filters, and there was no increase in efficiency as the smoke was deposited.

13. A few tests were made with woolen fabrics, but they proved to be no better as filters than cotton fabrics of similar texture.

14. The efficiency of the filters decreased somewhat with an increase in the rate of air flow. Sometimes a cotton fabric with a nap showed a decrease after humid smoke had wet it and the moisture had caused the fibers of the nap to adhere together.

15. The resistance of the filters to air flow increases in proportion to the number of plies of fabrics after the first ply. The first filter layer shows a somewhat higher resistance than the additional ones.

16. The resistance of fabric filters to air flow is very nearly proportional to the rate of air flow.

17. Air filters of high efficiency can be made with a sufficient number of plies of material that has a low efficiency per single ply—cheesecloth, for example. Such filters have less resistance to air flow than equally efficient filters made of fewer plies of the higher-efficiency materials, such as closely woven muslin.

18. The thicker filters of loose-textured material clog less rapidly than equally efficient filters composed of fewer plies of tightly woven material.

19. A new type of dust respirator was designed and constructed according to the principles brought out in the tests. This respirator consists of a large filter of canton flannel made into a cap or turban for the head. Air filters through the canton flannel to the interior, passes through a check valve, and is then conducted through a rubber tube running over the forehead and between the eyes to the nose, which is covered with a small rubber nose cap. At an air flow of 85 liters per minute the efficiency of this respirator is 58 per cent against tobacco smoke and 93 per cent against silica dust.

20. The data presented and the principles outlined may aid manufacturers in improving dust respirators.

21. Although the use of respirators should be encouraged among workers in dusty industries, a respirator can not be considered a final safeguard. In mining and in other industries efforts to prevent the formation of dust and its distribution by the air, by the use of hollow drill steel and water, and by sprays on the undercutting machines should be continued.

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